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Scientific Assessment Document on Status of Complex Terrain Dispersion Models for EPA Regulatory Applications

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The U.S. Environmental Project Agency is sponsoring the Complex Terrain Development program, a multi-year integrated effort to develop, evaluate, and refine practical plume dispersion models for calculating ground-level air pollutant concentrations that result from large emission sources located in mountainous terrain. At the present time, slightly more than halfway through the effort, a scientific assessment document on the status of complex terrain dispersion models for regulatory application has been prepared to inform potential users of the current availability of complex terrain dispersion models, and to describe the future products of the Complex Terrain Model Development program.

This assessment document summarizes the meteorological phenomena of importance to complex terrain modeling and describes currently available modeling techniques. Results from selected model evaluation studies and from related fluid modeling simulations are also presented. Based on this current state of model development, suggestions are presented for model improvements and for current and future research needs. The assessment document concludes with a summary of major findings and associated conclusions pertinent to the topic of complex Terrain dispersion modeling.

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SCIENTIFIC ASSESSMENT DOCUMENT ON STATUS OF COMPLEX TERRAIN DISPERSION MODELS FOR EPA REGULATORY APPLICATIONS

by

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The author, Francis A. Schiermeier, is on assignment to the Environmental Sciences Research Laboratory, U.S. Environmental Protection Agency, from the National Oceanic and Atmospheric Administration, U.S. Department of Commerce.

ABSTRACT

The U.S. Environmental Protection Agency is sponsoring the Complex Terrain Model Development program, a multi-year integrated effort to develop, evaluate, and refine practical plume dispersion models for calculating ground-level air pollutant concentrations that result from large emission sources located in mountainous terrain. The first objective of the complex terrain program is to develop models with known accuracy and limitations for simulating 1-hour average concentrations resulting from plume impingement on elevated terrain obstacles during stable atmospheric conditions.

The completion date for this initial model development effort is October 1986, at which time a validated model accompanied by documentation and user's guide is to be made available. At the present time, slightly more than halfway through the effort, a scientific assessment document on the status of complex terrain dispersion models for regulatory applications has been prepared to inform potential users of the current availability of complex terrain dispersion models, and to describe the future products of the Complex Terrain Model Development program.

This assessment document summarizes the meteorological phenomena of importance to complex terrain modeling and describes currently available modeling techniques. Results from selected model evaluation studies and from related fluid modeling simulations are also presented. Based on this current state of model development, suggestions are presented for model improvements and for current and future research needs. The assessment document concludes with a summary of major findings and associated conclusions pertinent to the topic of complex terrain dispersion modeling.

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SECTION 1

INTRODUCTION

This assessment document discusses the state-of-science of atmospheric dispersion modeling for "regulatory use" in regions of mountainous or complex terrain. For any type of terrain, regulatory applications of air quality models, as required by the Clean Air Act Amendments of 1977 and by EPA regulatory processes, place several requirements on the use and application of dispersion models. First of all, the regulations require that specific ambient air quality concentrations be maintained at the ground surface which includes mountain sides and crests. Secondly, the National Ambient Air Quality Standards (NAAQS) and Prevention of Significant Deterioration (PSD) increments are specified for various averaging times. For example, sulfur dioxide (SO_2) has ambient standards and increments for 3-hour, daily, and annual averaging periods. Furthermore, the 3-hour and daily ambient standards or increments for SO_2 must not be exceeded more than once per year at any location (these are commonly called the highest, second-highest values).

These attributes of the ambient standards require that dispersion modeling be applied to meet these needs. In practice, this has generally been accomplished by requiring that one or more years of appropriate meteorological data be input to a model and that output files be created to display the air quality concentration values needed for regulatory decisions. The need to utilize large quantities of meteorological input data, and the requirement to compute concentrations for each hour of a year or more, results in substantial computer costs for codes of significant complexity. Thus, there is considerable interest in the development of relatively simple and computationally-efficient algorithms to simulate transport and dispersion processes.

One of the most difficult regulatory applications for atmospheric dispersion models is the prediction of ambient air pollutant concentrations resulting from source releases in regions of complex or mountainous terrain.

The difficulties arise from the complexity of the source-receptor configurations and the wide range of unique effects that topography has on meteorological flows. The problem is important because, for reasons to be described, the presence of elevated topography often imposes more stringent limitations on emissions than for a similar source located in flat terrain. Furthermore, it has been common practice to locate pollutant sources at the bottoms of river valleys or adjacent to transitions from flat to mountainous terrain. Of special significance is the fact that a common setting for much of the energy development activities in the western United States is a source surrounded by mountainous terrain or at least having sufficiently high terrain features within distances subject to regulatory applications.

For releases from an elevated source located near terrain that may rise to elevations greater than the expected plume height, generally the most critical question is to quantify the magnitude of the plume concentrations expected on the face of the nearby terrain feature. The notion that the expected surface concentrations would be much larger than those that would be anticipated in flat terrain, and could be as large or larger than what would be expected along the elevated plume centerline, led early modelers (e.g., Van der Hoven et al., 1972) to develop simple, "direct-impact" models for computing concentrations on mountainsides. In the absence of more relevant data, flat terrain dispersion rate information was used. This type of computation would suggest that under very stable atmospheric conditions, ground-level concentrations for elevated releases near complex terrain might be one to two orders of magnitude larger than would be expected in the absence of the high terrain.

The magnitude of this difference inspired many scientists to examine the modeling issue more thoroughly. Indeed, over the past decade, a number of efforts have been undertaken to develop reliable methods for predicting concentrations in mountainous terrain (Egan, 1984a). In addition, as will be described in this document, findings that help quantify the differences to be expected between air quality concentrations in flat versus mountainous terrain have been identified. These findings include methods for more realistically estimating dispersion rates as might be modified by the presence of terrain as well as methods for estimating plume trajectories as affected by terrain objects.

In addition to the "plume impact" problem identified above, the presence of terrain affects air quality concentrations in a number of other ways. For example, flow separation and ensuing turbulence on the lee sides of mountains or hills affect the dispersion of releases from sources located downwind of these terrain features. Snyder (1983) suggested this effect may cause significant concentrations on the lee side of a hill under neutral stability. "Channeling" along the axes of river valleys affects the persistence of wind directions along such valleys. On the other hand, the "sheltering" effects of terrain features on the air flow within deep valleys often gives rise to prolonged stagnation episodes in such regions. Thus the complexities introduced by the presence of significant terrain features are large and the effects they have on an individual source depend very much on the specific location of the source, its proximity to terrain, and the specific nature of the terrain features. Important differences can be expected, for example, for flow toward isolated features versus flow toward mountain ridges and as a function of the height of the terrain features relative to expected plume elevations. The need to have a better technical understanding of the implications of these effects has been matched by significant attention from the scientific and regulatory communities. In this context, it is relevant to review briefly three technical workshops that have taken place within the last several years on these topics.

In 1976, the U.S. Energy Research and Development Administration sponsored a workshop on "Research Needs for Atmospheric Transport and Diffusion in Complex Terrain" (Barr et al., 1977). The workshop report recommended that a multi-year program be initiated to address the air quality assessment aspects of oil shale development in the western United States and other energy conversion developments in regions of complex terrain. The workshop recommendations form the basis for the ongoing Atmospheric Studies in Complex Terrain (ASCOT) program (Dickerson and Gudiksen, 1980) sponsored by the U.S. Department of Energy (DOE). This program has focused on the dispersion of near-surface releases in regions of complex terrain and how such releases would be affected by mountain-valley circulations and drainage winds. Field experiments have been performed in the geysers geothermal area of northern California and in other locations in Washington, Colorado, and New Mexico. The research efforts will result in a series of descriptions and mathematical models for use in assessing the effects of local flows in dispersing low-level releases in valley situations.

To address the issues of most concern to power plants and other facilities with significantly elevated releases, the U.S. Environmental Protection Agency (EPA) sponsored a "Workshop on Atmospheric Dispersion Models in Complex Terrain" in 1979 (Hovind et al., 1979). Contributions to this workshop provided the technological basis for a series of field measurements, fluid modeling experiments, and mathematical model development efforts needed to develop reliable dispersion modeling techniques for complex terrain (Holzworth, 1980; Schiermeier et al., 1983b). An outgrowth of the workshop recommendations is the ongoing EPA-funded Complex Terrain Model Development program which has as its first objective the development of models with known accuracy and reliability for simulating 1-hour average concentrations resulting from plume impingement on elevated terrain obstacles during stable atmospheric conditions. This topic was chosen in order to focus on a major regulatory problem upon which available resources could demonstrate significant progress. Future objectives of the program may include extension of the complex terrain model development effort to increased topographical complexity, to neutral and unstable atmospheric stabilities, and to longer averaging periods.

In 1983 under EPA sponsorship, the American Meteorological Society (AMS) conducted a "Workshop on Dispersion in Complex Terrain" (Egan, 1984b) for purposes of evaluating information gained from field measurements, fluid modeling simulations, and model development efforts undertaken during the past few years. This particular workshop also provided the opportunity to draw on the expertise of scientists doing related work but not directly participating in any major ongoing field experiments.

The Electric Power Research Institute (EPRI) has undertaken a comprehensive Plume Model Validation and Development (PMV&D) effort (Bowne et al., 1983) based on extensive field measurements. EPRI has completed experiments at power plants located in flat terrain and in moderately complex terrain, and plans to perform an experiment in a full complex terrain setting where the stack height would be less than the height of nearby terrain.

The interest and activity in complex terrain modeling is manifested by the fact that about one-sixth of the papers at recent AMS conferences on turbulence and diffusion and on air pollution meteorology have related to complex terrain studies. These papers are about equally divided between theoretical development and application-oriented topics. Because of the site-specific nature of much of the work performed to date, a challenge for researchers in this field is to systematically separate general conclusions from those findings that are more likely to be very much site specific. This document will attempt to identify some of the most significant general advances in our understanding of this topic.

The remainder of this report will describe the status of complex terrain modeling, with attention paid to aspects of the problem pertinent to EPA's regulatory applications of dispersion models. The document will identify and describe the meteorological dispersion phenomena of most importance in complex terrain, drawing heavily from the findings of the 1983 AMS workshop on this topic. Available modeling techniques applicable to regulatory needs will be summarized, and evaluation studies performed to date on applicable models will be described. The application of fluid modeling techniques will be discussed, focusing on the contributions that these studies have made to the understanding of flow dynamics as affected by terrain features. Directions for model improvements and future research needs will be identified.

SECTION 2

METEOROLOGICAL PHENOMENA OF IMPORTANCE

In this section, meteorological phenomena that are of special importance (if not unique) to the problem of estimating air quality impacts of sources located in or near complex terrain are described. Because the descriptions often suggest or reflect mathematical algorithms, these are presented here as appropriate. In the remainder of this document, the term "hill" is used generically, with two- and three-dimensional ridges considered as specific types of hills.

PLUME INTERACTION WITH WINDWARD-FACING TERRAIN FEATURES

Flow Parameters Affecting Plume Trajectories

If a stack is located near a hill that is taller than the stack, the possibility exists that the highest concentrations to be expected in the area will occur on the hillside when the airflow is from the stack toward the hill. These high concentrations would be expected either by direct plume impaction during certain stable conditions, or by near misses as the streamlines pass close to the hill during other stable, neutral, or unstable conditions.

The presence of mountainous terrain has several effects on the flow upwind of and above the obstacles. Terrain acts to distort the flow field causing deflections, accelerations/decelerations, and associated contractions/expansions of "stream tubes" of air. It also acts to alter the structure of turbulence within the region of flow near the surface. The dynamics of the flow field upstream of a hill depends critically on the ambient density (or temperature) stratification. In stable conditions, vertical motions of air parcels are opposed by restoring buoyancy forces. The stratification effect can be characterized by a Froude number, Fr, given by

$$Fr = U/Nh \qquad (1)$$

where U is a characteristic wind speed for the upstream flow; N is the Brunt-Vaisala frequency given by

$$N = [-(g/\rho)(\partial\rho/\partial z)]^{\frac{1}{2}}; \tag{2}$$

g is the gravitational acceleration; ρ is the air density; and h is the hill height. The Froude number squared can be interpreted as a ratio of inertial to buoyancy forces in a fluid. Moderate to neutral stability (dominated by inertial effects) includes the range $1 < Fr < \infty$, whereas strongly stable conditions (dominated by buoyancy effects) encompass the range $0 < Fr < 1$.

One of the outstanding features of strongly stable flow about three-dimensional hills is the passage of fluid around the hill in essentially horizontal planes below some height H_c, which depends on the stratification. Above this height, fluid passes both over and around the hill. The height H_c is commonly called the "critical height" or "dividing-streamline height". The idea of a region of horizontally layered flow was first described theoretically by Drazin (1961) for axisymmetric hills and was later confirmed in laboratory experiments for similar geometries by Riley et al. (1976), Brighton (1978), and perhaps most convincingly by Hunt et al. (1978). The last authors showed experimentally that for a uniform upstream velocity profile and a constant density gradient, H_c is given by

$$H_c = h(1-Fr). \tag{3}$$

This formula is consistent with a simple energy balance argument for an air parcel as first put forth by Sheppard (1956). Sheppard postulated that for a given environmental lapse rate, one could calculate the value of horizontal velocity far upwind that would enable air to just surmount a hill by equating the kinetic energy of a fluid parcel upwind to the potential energy change associated with lifting the parcel to the hillcrest. Snyder et al. (1982) have extended this argument to arbitrary velocity and density profiles with the result

$$\frac{1}{2}\rho U^2(H_c) = g \int_{Hc}^{h} (h-z) \left(-\frac{\partial\rho}{\partial z}\right) dz \tag{4}$$

where H_c must in general be determined iteratively.

For ideal two-dimensional ridges or very long finite ridges, the fluid can be blocked (i.e., effectively become stagnant) ahead of the obstacle. For these geometries, a well-accepted formula for the dividing-streamline height does not yet exist. In addition, there is ambiguity about the upstream extent of this blocked region and its variation in depth with upstream distance.

The simple energy argument of Sheppard (1956) assumes that an air parcel has a zero horizontal velocity at hilltop. However, this assumption is inconsistent with observed flow fields which show that fluid flow accelerates at the top of the hill. A more complete model is required to explain adequately this speedup phenomenon and to ensure reliable extension of the H_c concept to geometries more complex than simple hill shapes. For example, if the stratification continues to the mountaintop (h), the hydrostatic solution of Smith (1980) is probably more applicable than potential flow solutions. The main difference is an earlier lifting of the flow (perhaps decreasing the windward-side concentrations).

At elevations below H_c, the straight-line flow will be deflected by the terrain feature. The plume will tend to go to one side or the other and may oscillate back and forth, being very sensitive to upstream flow direction. Large ground-level concentrations are expected near this level as well as large apparent lateral diffusivity.

Dispersion in Strongly Stratified Flow

Strongly stratified flow below H_c has insufficient kinetic energy to pass over a hillcrest and, neglecting wind shear effects, such flows can be considered essentially horizontal as they pass around a hill. When a plume is directly along the stagnation streamline, the plume will "impinge" on the hill resulting in concentrations as large as those in the elevated plume's center.

Along the stagnation streamline, flow diverges as it approaches the hill. Hunt et al. (1979) show that the large increase in the crosswind dispersion coefficient, σ_y, caused by diverging streamlines, is almost compensated by the decrease in wind speed, U, as the stagnation point is approached, and that at the stagnation point, $\sigma_y U$ is approximately the same as it would have been in the absence of the hill. These arguments suggest that the concentration at the stagnation point is approximately equal to that which would occur in the plume without the hill. However, effects of plume meander due to larger-scale eddies in the flow upwind of the hill need to be considered explicitly as described below.

Surface concentrations at an assumed point of impingement or stagnation can be estimated during plume meandering conditions by integration over the changes in wind direction. During any single quasi-steady period, denoted by the subscript i, the concentration at the stagnation point due to a plume with horizontal angular spread of α_{si} will be nonzero only if the mean wind direction during the period lies within $\alpha_{si}/2$ of the stagnation streamline ($\theta_i = \theta_s \pm \alpha_{si}/2$). If this concentration is denoted by $C_i(\theta,\theta_s)$, then the average hourly concentration C at the stagnation point is given by

$$C = \int_\theta C_i(\theta,\theta_s)P(\theta)d\theta \tag{5}$$

where $P(\theta)$ is the hourly probability density function of wind directions. If the wind speed, vertical plume spread, and horizontal plume spread angle are nearly constant among quasi-steady periods during the hour, then the only nonzero contributions to the integral in Equation 5 arise for wind directions within $\pm\alpha_s/2$ of the stagnation wind direction. Furthermore, if the concentration distribution within the plume during each quasi-steady period is assumed to be uniform, and if the spread due to plume meander during the hour is much greater than α_s, so that $P(\theta)$ is nearly constant within the interval α_s, then

$$C = \bar{C}_i \int_{\theta_d-\alpha_s/2}^{\theta_d+\alpha_s/2} P(\theta)d\theta = \bar{C}_i P(\theta_d)\alpha_s \tag{6}$$

where $\bar{C}_i = Q/\sqrt{2\pi}\,\sigma_z U \alpha_s x$;

U, σ_z and α_s represent averages for the relevant hour; and x is the distance from the release to the stagnation point. Note that if $P(\theta)$ is Gaussian, then

$$C = \frac{Q}{\sqrt{2\pi}\,\sigma_z U \sigma_\theta x} \exp\left[-\frac{(\theta_m-\theta_s)^2}{2\sigma_\theta^2}\right] \quad (7)$$

where σ_θ is the standard deviation of the wind direction about the mean direction θ_m. In practice, $P(\theta)$ is specified by the histogram of observed distribution of winds during each hour.

Experimental Evidence

Snyder et al. (1982) have demonstrated the validity of the integral formula (Equation 4) using laboratory simulations under stably stratified conditions. These tests were made at the EPA Fluid Modeling Facility at Research Triangle Park, North Carolina and in the stratified wind tunnel at the Japan Environment Agency. The concept of H_c was examined for bell-shaped hills, a cone and hemisphere, triangular ridges, vertical fences, and for a scale model of Cinder Cone Butte. Snyder and his co-workers have concluded that the integral equation for estimating H_c accurately predicted the separation of the flow regimes.

The EPA-sponsored Small Hill Impaction Studies, conducted at Cinder Cone Butte near Boise, Idaho and at Hogback Ridge near Farmington, New Mexico (Lavery et al., 1983a), have also shown that the integral formula for H_c discriminates between the flow regimes for both an isolated axisymmetric hill (Cinder Cone Butte) and a two-dimensional ridge (Hogback Ridge). Photographs of oil-fog plumes along with SF_6 (sulfur hexafluoride) and CF_3Br (trifluoromonobromomethane) ground-level concentration patterns clearly distinguished between the horizontal flow and the flow that goes over the hills. The H_c concept and its ability to predict whether plumes impinge upon a hill and pass around it, or travel up and over a hill, were also found by

Ryan et al. (1984) to be valid at Steptoe Butte, a large isolated hill in eastern Washington; by Rowe et al. (1982) at Copithorne Ridge, a 6-km long ridge in Alberta; and by Wooldridge and Furman (1984) at San Antonio Mountain in New Mexico.

An analysis of the observed tracer gas concentrations and the meteorological data obtained at Cinder Cone Butte showed that the highest C_0/Q (concentration/emission) occurred when the release height, H_s, was near or slightly higher than H_c. During this situation, the plume was transported directly toward the hill and produced high ground-level concentrations. Lower elevation releases tended to be transported around the hill sides and releases well above H_c were transported up and over the hillcrest. Figure 1 shows the C_0/Q values versus $1-H_c/H_s$ for each hour of Cinder Cone Butte tracer data. The highest normalized concentration occurred when $H_s \sim H_c$.

The Hogback Ridge experiment also showed that H_c discriminates between the flow regimes, although the nature of the flow below H_c is still under investigation. A preliminary analysis of 34 tracer-hour concentrations showed that the highest observed C_0/Q occurred when $H_s \leq H_c$ as shown in Figure 2. Since Hogback Ridge is basically two-dimensional, the higher values could be explained by the highly variable and generally stagnant flow below H_c and, if the average wind were directed toward the ridge, the tracer gas would be transported directly to a sampler near the release elevation.

Thus, there appears to be consistent agreement between field and laboratory observations on the flow structure upwind of a three-dimensional hill, in particular the horizontal nature of the flow below H_c and the dependence of H_c on stratification. This is true for axisymmetric hills and for hills with small aspect ratios where width/height ~ 10 (Snyder et al., 1982). Field experiment verification is still needed to confirm the validity and applicability of the dividing-streamline concept for terrain features greater than a few hundred meters in height.

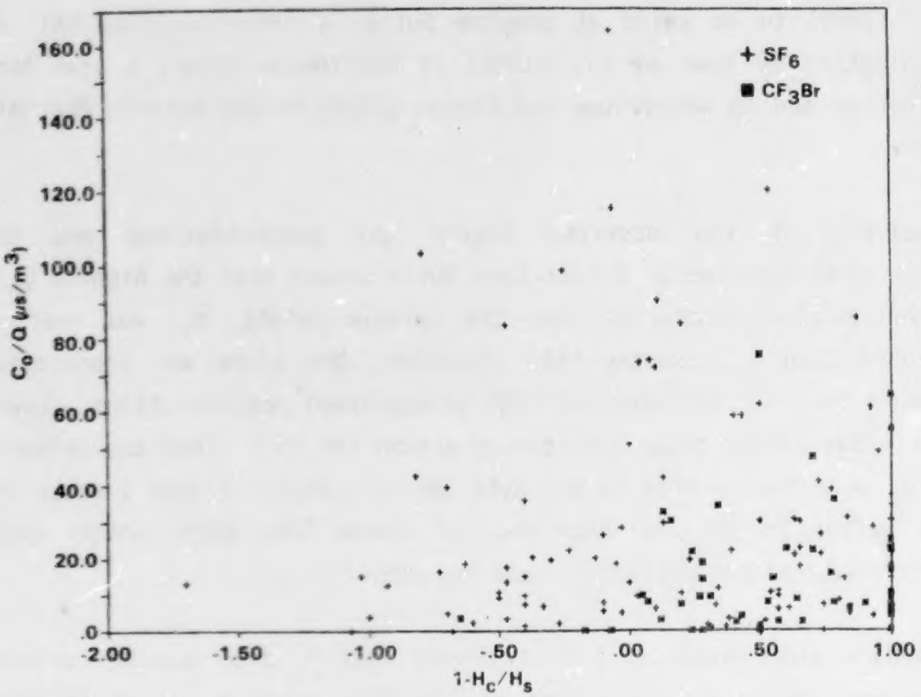

Figure 1. Maximum hourly observed concentrations normalized by emission rate versus 1-H_c/H_s for 153 hours of Cinder Cone Butte tracer data.

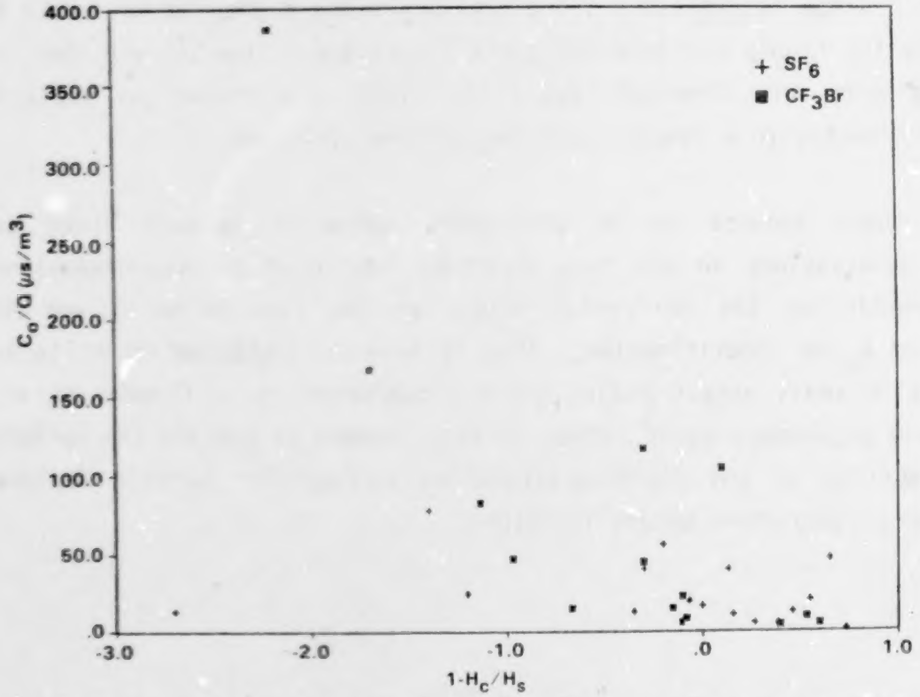

Figure 2. Maximum hourly observed concentrations normalized by emission rate versus 1-H_c/H_s for 34 hours of Hogback Ridge tracer data.

Flow Over Terrain During Neutral Conditions

It is generally accepted that the first-order effects of terrain on altering the flow on the windward face during neutral conditions can be estimated using modifications to potential flow theory (Hunt and Mulhearn, 1973; Hunt et al., 1979). For regulatory applications, a practical approach involves the superpositioning of Gaussian plume spread onto trajectories determined by potential flow approximations (Isaacs et al., 1979; Hunt et al., 1979). Egan (1975) demonstrated that the "half-height" terrain correction factor followed from considerations of potential flow over a sphere, but a "terrain-following" plume assumption provided first-order estimates for neutral flow over a two-dimensional (ridge-like) shape. Neutral conditions often are associated with high wind speeds and synoptically persistent meteorological conditions. Thus, neutral conditions can be of importance to the maintenance of 24-hour average ambient air quality standards or Prevention of Significant Deterioration (PSD) increments, especially where channeling effects of terrain features are important.

Dispersion During Unstable Conditions

For most regulatory applications, "worst case" conditions for sources close to high terrain are expected to occur during stable or neutral conditions. For this reason, phenomena during unstable conditions have not been studied in depth. Because of the differential heating of mountain slopes during daylight hours, convection effects result in sustained and significant updrafts and downdrafts. Also "fumigation" of pollutant material onto hilltops in mid to late mornings has been observed to result in short durations of high concentrations. For unstable conditions, currently available models generally use the flow trajectories derived for neutral dispersion.

Turbulence Levels in Regions of Complex Terrain

In general, turbulence levels are expected to be higher over complex terrain than over level terrain for a given atmospheric stability class, itself sometimes difficult to estimate reliably over the depth of flow. These enhanced turbulence levels are most likely a result of three factors:

(a) Nocturnal, radiational cooling that produces surface inversions is often coupled with very low wind speeds in level terrain and is likely to result in the generation of gravity-driven drainage flows in complex terrain. These flows result in the mechanical production of turbulence and time-dependent, nonstationary secondary motions which periodically sweep the terrain. It is likely that peak concentrations result from these time-dependent movements rather than from the near-stationary drainage flows.

(b) Topographic alteration of flow direction and speed will result in the production of shear in all directions, which not only contributes to the production of turbulence but results in large flow meandering.

(c) In complex terrain the presence of flow stratification is a key element in the production of rapid flow accelerations and decelerations, lee waves, and rotors, which tend to produce shearing motions and regions of flow reversal. During neutral and unstable atmospheric conditions, the effects of terrain on altering turbulence levels appear to be smaller than during stable conditions (Start et al., 1974).

Lateral turbulence levels in complex terrain are generally enhanced to a greater extent than vertical turbulence. Observations of smoke plume meandering and uplifting are reasons cited to justify an increase in horizontal dispersion rates. When the atmosphere is stably stratified, generalizations are more difficult. Air parcels downwind of a ridge may be rapidly dispersed upward (or even upwind) by rotor zones or other eddy motions associated with lee-side phenomena (Van Valin et al., 1982). Under stable conditions, ridge-shaped terrain features can contribute to large-scale stagnation of the air flow in lower upwind regions, resulting in very low winds with little net transport of pollutant material into or out of the region. This topic will be discussed further in the context of phenomena within valleys.

PLUME INTERACTION WITH LEE SIDES OF TERRAIN FEATURES

Previous discussion has focused on the phenomena of importance in determining ambient air quality concentrations on upwind-facing slopes. Fluid modeling shows that high concentrations can also be expected for certain meteorological conditions on back-facing or leeward slopes of terrain features downwind of a source. Field measurements are uncommon for these situations because regulatory requirements have generally focused on gaining information on the upwind-facing slopes nearest to a pollution source. This section provides a brief overview of the current understanding of flow in the lee of hills.

Lee-Side Flow During Neutral Conditions

Simple flow models, e.g., potential flow coupled with rapid distortion theory, work reasonably well for predicting surface concentrations on the upwind faces of hills, both two-dimensional and three-dimensional. However, these simple models are inadequate for predicting wake effects, even for hills of moderate slope (i.e., 15° for two-dimensional and 25° for three-dimensional hills), let alone for steep hills with separated wakes. Flows on the lee sides of hills are among phenomena expected to cause high ground-level concentrations in the vicinity of terrain and for which no routine model simulation techniques are available.

Snyder (1983) summarized a variety of idealized neutral-flow wind tunnel studies in which plumes from stacks located both upwind and downwind of various terrain shapes produced ground-level concentrations on or downwind of the obstacle many times higher than would be expected if the terrain were not present. When expressed in a ratio, this increased concentration over the no-obstacle concentration is termed the "terrain amplification factor", specifically defined as the ratio of the maximum concentration occurring in the presence of the hill to the maximum concentration that would occur from the same (elevated) source if it were located in flat terrain.

Fluid modeling experiments in simulated neutral atmospheric boundary layers showed that plumes released downwind of variously shaped two-dimensional hills resulted in amplification factors as large as 10 to 15, whereas plumes released upwind of the hills produced factors of 2 to 3 (see Section 5). Two lee-side phenomena were observed to produce high factors. One was downwind of a relatively steep hill (26°) where the flow separated steadily near the top of the lee side and reattached on the surface downwind of the base. In this case, pollutants from sources located on the separation/reattachment streamline were advected directly to the ground, producing very large terrain amplification factors.

The other case was downwind of a hill of moderate slope (16°). Here, the flow separated intermittently but not in the mean. Pollutants downwind of this hill were thus subjected to very small mean transport speeds and very large turbulence intensities. This resulted in rapid diffusion directly to the surface and consequently to large amplification factors. High amplification factors were also observed on the lee sides of three-dimensional objects, especially when plumes were released near the separation-reattachment streamlines. In the three-dimensional cases, higher across-wind aspect ratios generally produced higher terrain amplification factors.

Fluid modeling results indicate that typical downwind lengths of reversed flow regions are 10 hill heights for two-dimensional hills and 2 to 10 hill heights for three-dimensional hills. In addition, strong trailing vortices downwind of three-dimensional hills have been observed in laboratory studies. The strong downwash caused by these vortices has also resulted in large surface concentrations.

Stratified Flow in Lee of Hills

Under strongly stratified flows, effluents released below the dividing-streamline height on the lee sides of hills have been observed to be recirculated to the hill surface and to cover a narrow vertical band spread over a nearly 180° sector of the hill surface. Whereas instantaneous concentrations from downwind sources are observed to be considerably lower than impingement concentrations from upwind sources, long-term average concentrations from these downwind sources may be larger than impingement concentrations because the wind meander will significantly reduce time-averaged impingement concentrations, but not the lee-side concentrations. Even simple models for predicting lee-surface concentrations from downwind sources are not readily available.

DISPERSION OF PLUMES IN VALLEY SITUATIONS

Many air pollution sources such as cities, roads, industrial operations, and energy production facilities are located in mountain valleys. It has been recognized for at least 40 years (Hewson and Gill, 1944) that air pollution problems can arise from these sources as a result of the special meteorological processes that occur in valleys.

The AMS workshop attendees separated the discussion of the dynamics of individual plumes interacting with high terrain from discussions of these latter special flow conditions associated with valley settings (Egan, 1984b). The processes identified as important to valley situations include nocturnal drainage flows, fumigation, flow channeling by valley sidewalls, and persistent low wind speed, stable flows. For purposes of discussion, it is convenient to distinguish between relatively shallow valleys, deep draining valleys, and closed valleys.

Shallow Valleys

Shallow valleys are defined by comparison with the effective height of a plume from a source affecting air quality in the valley. A valley is shallow if the plume is significantly higher than the terrain features. Under these conditions, the plume is cut off from the valley boundary layer during stable conditions and reacts in a manner analogous to a plume over flat terrain.

Although the trajectory of the plume may be steered somewhat by the valley orientation, the centerline of the plume is higher than the valley sides or ridges forming the valley.

Preliminary results from the EPRI PMV&D project tracer studies at the Bull Run Generating Station in Tennessee indicated that terrain influences on lifting of plume paths were not observed because the plumes from the facility usually followed trajectories that were parallel to the valley axes. The PMV&D measurements were made when the plume centerline was significantly higher than the terrain features (Reynolds et al., 1984).

Deep, Draining Valleys

Scientific investigations have thus far focused primarily on improving our understanding of the physics of valley meteorology, although a few important research studies have focused directly on air pollution investigations (e.g., Hewson and Gill, 1944; Start et al., 1975). An improved understanding of valley nocturnal drainage flows is now becoming available from the DOE ASCOT program (Dickerson and Gudiksen, 1983; Gudiksen and Dickerson, 1983). Other work has focused on the breakup of nocturnal valley temperature inversions in deep valleys (Whiteman, 1980). This work has led to a thermodynamic model of temperature inversion breakup (Whiteman and McKee, 1982) and more recently, to an initial model of air pollution concentrations produced on the valley floor and sidewalls due to post-sunrise fumigations of elevated nocturnal plumes (Whiteman and Allwine, 1983). In these studies, the effects of convective boundary layers that grow over heated valley surfaces after sunrise, the effects of upslope flows produced over the sidewalls, and the effects of compensating subsiding motions over the valley floor have been simulated but need more field evaluations.

In actual valleys, topographic complications can be expected to greatly influence the development of local circulations and the dispersion of pollutants emitted within the valley. The diversity of valley shapes, orientations, and the presence of tributary valleys and terrain constrictions along the valley axes can be expected to influence the development of the along-valley circulations, turbulence levels, and other important aspects of valley meteorology.

Closed Valleys

Certain valleys with weak or obstructed outflow have been characterized as trapping valleys, in contrast with draining valleys with vigorous outflow. The accumulation of cool air draining from the sides of the trapping valleys will build up a deep stable layer during nighttime hours that is capped by a stronger inversion at the interface with the above-valley air near the top of the cold pool. Pollution plumes emitted into this domain are likely to be confined within this temperature structure and the valley sidewalls.

In addition to diurnal trapping regimes, certain synoptic conditions produce stagnation episodes. High pressure systems characterized by low wind speeds, clear or foggy skies, subsidence inversions, and nocturnally-produced ground-level inversions, may exist for 4- to 5-day periods. During these episodes, additional emissions are not compensated by flushing so that air quality continually degrades. The pollution conditions are not stationary as is evidenced by sloshing of pollution centers around the valley. The DOE ASCOT program characterized diurnal pooling and stagnation within one California valley in 1979 and 1980 (Gudiksen and Dickerson, 1983).

The shape of a closed valley creates unique flow regimes. Limited field data show that nighttime radiational cooling of the surrounding mountain slopes can create a downslope drainage flow that appears to reach maximum strength just prior to local sunrise. The drainage flow tends to move toward the lowest point in the valley. Available data are inadequate to determine if a gyre usually develops over the valley low point prior to sunrise. Other observations indicate that material released at ground level within a closed valley at night can be transported out of the valley, a phenomenon that is difficult to explain physically. More information is needed to permit a quantitative description of the behavior of effluents released into thermally stratified closed valleys.

CONVECTIVE CIRCULATIONS IN COMPLEX TERRAIN

In flat terrain, convective flows frequently lead to the fumigation of pollutants trapped aloft or the early downwash of a looping plume, resulting in high ground-level concentrations. Convective flows developing over hills, ridges, or more complicated terrain may significantly alter streamline patterns, separation and stagnation locations, and hill wake turbulence. It is possible that nonhomogeneous radiative heating caused by slope orientation could result in different convective scales than commonly associated with horizontal terrain. These perturbed spatial and temporal scales could result in worst-case ground-level concentrations from lee impingement, sudden subsidence, or downdrafts.

RELATED FIELD STUDY OBSERVATIONS

Most of the complex terrain meteorological phenomena described in this section have been observed in various field studies conducted during the past couple of decades. The more recent studies have been designed specifically to advance the science of complex terrain modeling, while some of the earlier studies were performed primarily to determine the efficacy of tall stacks in reducing nearby ground-level pollutant concentrations. In the remainder of this section, a few of these field studies are described to illustrate actual observations of the meteorological phenomena important to complex terrain plume dispersion.

Large Power Plant Effluent Study

The EPA conducted a comprehensive field study in western Pennsylvania between 1967 and 1972 to determine the extent and effects of power plant emissions from tall stacks at the Keystone, Homer City, and Conemaugh Generating Stations (Schiermeier, 1972a, 1972b). The meteorological portion of the Large Power Plant Effluent Study (LAPPES) was conducted along three interrelated lines of investigation: (1) determination of plume rise under a variety of atmospheric conditions; (2) determination of plume dispersion, both vertical and horizontal, as a function of downwind distance and atmospheric conditions; and (3) determination of the magnitude, areal extent, and occurrence frequency of SO_2 concentrations at ground level.

A distinct advantage of this location for the study was that air quality measurements progressed as each stack of each generating station became operational. The 1967 and 1968 LAPPES field studies were conducted in an area surrounding the Keystone Station. Beginning in 1969, the project area was expanded to encircle the Homer City Station as it became operational, with similar expansion effected in 1970 to include the Conemaugh Station.

The generating stations are located in the Chestnut Ridge sector of the Allegheny Mountains. Typical of this area of Pennsylvania are numerous creeks and rivers, and rolling hills rising 100 to 200 m above the valley floors. This land, much of which is tree covered, slopes generally upward to the east to form the foothills of the Allegheny Mountains. Prominent features include the Chestnut Ridge, oriented northeast-southwest and situated between the Homer City and Conemaugh Stations, and the considerably higher Laurel Ridge immediately southeast of the Conemaugh Station.

The Conemaugh Station was most susceptible to topographic influences. Separating this plant from Johnstown is the Laurel Ridge with some peaks within 6 km ranging up to 200 m above the two 305-m tall stacks. During the October 1970 measurement series, and to a lesser extent during the October 1971 series, helicopter and ground-based measurements confirmed the unique dispersion characteristics in the area. With moderate to strong flow from the southeast quadrant, the plume was brought to the surface within a few hundred meters of the stacks. The SO_2 concentrations at the surface rapidly diminished with distance to the northwest but increased slightly on the lee side of Chestnut Ridge, about 12 to 14 km from the Conemaugh Station. In addition to ground-level SO_2 measurements, this downwash on the lee side of Laurel Ridge was confirmed by actual subsidence of pilot balloons in the vicinity of the Conemaugh stacks.

Accompanying this downwash phenomenon was a persistent cloud cover over the Conemaugh Station, caused by upslope action over Laurel Ridge. Observed cloud bases varied between 450 and 650 m above stack base elevation with coverage ranging from scattered to overcast, although usually broken. This cloud deck frequently extended as far northwest as Chestnut Ridge, with clear skies beyond. The lee downwash appeared to be associated with neutral flow because on days when the cloud cover dispersed sufficiently to allow surface heating, the downwash ceased and the plume rose in a normal manner.

With winds from the opposite direction, i.e., the northwest quadrant, the plume rose over Laurel Ridge and apparently mixed through a deep layer in the lee of the ridge; relatively low concentrations were measured from ground level to the upper limit of sampling imposed by cloud bases. If a lee-wave phenomenon existed with northwest winds, it was not detected by the prevailing sampling methods.

During the April 1971 series, the Conemaugh plume was discovered to be intercepting ridges at considerable distances from the plant (11 to 20 km) and flowing smoothly down the lee side for about 1 or 2 km before rising again. That this phenomena was not confined to a particular wind direction was evidenced by the various azimuths of occurrence, i.e., 275, 327, 353, and 060 degrees. Two meteorological characteristics common to all four occurrences were the presence of strong surface inversions near the Conemaugh Station shortly after sunrise and the sudden disappearance of the high ground-level SO_2 concentrations in the lee of the ridges as surface heating commenced.

Widows Creek Power Plant Study

The Tennessee Valley Authority (TVA) increased the stack heights at their existing power plants during the 1970's in an effort to mitigate the problems of plume impingement on surrounding high terrain. However, the presence of the underlying complex terrain still affects general wind-flow patterns and turbulence levels at plume height. Data from TVA's Widows Creek Power Plant in Alabama were studied to determine these effects (Hanna, 1980). This plant is in a river valley with ridges rising 300 m above the valley floor at distances of 3 km from the plant. Stack heights are 152 m and 305 m.

The most obvious effect of the terrain was a strong channeling of the air flow in the valley, with cross-valley winds occurring only a small percentage of the time. In contrast, at plume elevation (ridge-top and above) the observed wind rose showed nearly uniform frequencies for all directions. If the wind-direction data from the valley meteorological tower were used to model environmental effects, they would obviously give a distorted picture of the true impact of the plume.

The second important effect of the terrain was an enhancement of turbulence (as measured by σ_θ) for cross-valley wind directions. By plotting observed σ_θ as a function of wind direction for neutral conditions, it was determined that cross-valley σ_θ observations were about 60% larger than along-valley σ_θ observations. This increase was probably due to the presence of persistent low-frequency eddies set up by the hills. The use of observed σ_θ values in Pasquill's formula, $\sigma_y = \sigma_\theta \times f(x)$, results in good agreement with σ_y determined from SO_2 concentration observations at monitors located on the nearby ridge.

Steptoe Butte Field Study

An EPA-sponsored study of wind flow and diffusion around an isolated 335-m hill (Steptoe Butte, Washington) was conducted in 1981 by scientists at Washington State University. The aims and experimental methods of this project were similar to those of the EPA Cinder Cone Butte experiment. The main differences between the two experiments were that there were limited meteorological profiles at Steptoe Butte, but a wider range of atmospheric stabilities was considered. Also, there were no measurements of the plume aloft at Steptoe Butte. Twenty-one tracer tests were conducted, with release heights ranging from the surface to about 190 m. A description of the experiments with results of preliminary analysis of the data is given by Ryan et al. (1984) and an analysis of the dividing streamline is discussed by Ryan and Lamb (1984). Testing of diffusion models with the data is not yet complete.

A qualitative analysis of the maximum plume impact showed that more than half of the concentration maxima occurred on the leeward half of the hill, although highest concentrations occurred on the upwind half. The position of the maxima rapidly shifted to the side of the hill as the horizontal displacement of the source from the flow centerline increased. The magnitude of these concentrations agrees fairly well with the predictions of potential flow models for flow around a cylinder or a hemisphere.

Ryan and Lamb (1984) pointed out that the vertical temperature structure at Steptoe Butte was more complex than at Cinder Cone Butte and attributed this difference to the greater hill height (335 m versus 100 m). This complexity influenced the calculation of the dividing-streamline height, which is a function of the Froude number. Several approaches were tried, including the use of a single hill Froude number (calculated over the full hill height), a local Froude number (calculated using local temperature gradients), and iterative solutions of the energy equation. The last method was found to be more appropriate for stable conditions with complex vertical temperature structures.

Tracy Power Plant Preliminary Study

The Tracy Power Plant near Reno, Nevada has been selected as the site for the 1984 Full Scale Plume Study, the third field experiment in the EPA Complex Terrain Model Development program. The Tracy plant is operated by Sierra Pacific Power Company. It has three units capable of generating 53, 80, and 120 megawatts (MW). The 120-MW unit is serviced by a 90-m stack which was used to release oil-fog and SF_6 during a preliminary experiment in 1983.

The plant is located about 40 km east of the Reno-Sparks metropolitan area in the Truckee River Valley of the Sierra Nevada Mountains. Peaks rise to elevations of 900 m above the stack base elevation within 6 km of the plant. The Truckee River enters the valley through a narrow opening, flows eastward just north of the plant, and then takes an abrupt turn to the north about 4 km east of the plant. The river flows between two mountains at its northward bend. The two mountains were the primary target areas for the dispersion experiments.

The preliminary flow visualization and tracer study that was conducted during November 1983 was co-sponsored by the EPA and EPRI. The experimental methods were similar to those used and tested at Cinder Cone Butte and Hogback Ridge and at the two previous EPRI field sites. Ten experiments were conducted for 73 hours during the preliminary study.

An analysis of the data base suggested the occurrence of stable plume impingement. SF_6 concentrations were observed during stable conditions on the target mountains east of the plant as well as on the hills to the west. The highest SF_6 concentrations were observed on the southwest corner of one target mountain. The elevations of the samplers that captured plume material were a few meters below the calculated hourly values of H_c. During other hours of stable plume impingement conditions, plume material was observed to stay below H_c. In short, it appears that the concept of a dividing-streamline height will be useful to distinguish flow regimes and to help simulate observed tracer gas concentration patterns in the Tracy area.

Drainage winds and katabatic effects were seen to produce ground-level concentrations on the valley floor in the gorge where the Truckee River bends to the north. Visual observations, photographs, and acoustic sounder records all suggested the turbulent transport of "old" plume material from aloft to the valley floor. The fumigation of oil-fog by drainage winds was also observed on the south side of one target mountain. These katabatic effects were not observed at Cinder Cone Butte or Hogback Ridge and must be accounted for in modeling this full-scale site.

The meteorological measurements depicted very complicated wind flows during the November experiments. Horizontal and vertical wind shears were common. These were probably caused by the combined effects of the complex terrain and migratory anticyclones and cyclones moving over the area in November. Persistent, windy neutral conditions produced ground-level concentrations in the area south of the target mountains. These conditions are similar to those in flat terrain, high-wind cases. The elevated terrain often channeled plume material between peaks and through low-lying draws, as verified by observations and photographs.

In summary, the Tracy preliminary study captured a variety of meteorological events and dispersion conditions. Stable flows, which can be described by the dividing-streamline concept observed at Cinder Cone Butte and Hogback Ridge, were also observed at the Tracy site. Other events, e.g., drainage winds and terrain channeling, more common to "full-scale" sites were also observed. For these reasons, the Tracy data base is expected to be useful in testing new dispersion concepts and in extending the modeling to conditions typical of a full-scale site (Strimaitis et al., 1984).

Brush Creek 1982 Field Tracer Study

A set of atmospheric tracer experiments was conducted during the summer of 1982 as part of the EPA Green River Ambient Model Assessment program. These experiments were performed in the Brush Creek Valley of Colorado in conjunction with the DOE ASCOT research program. The EPA portion of the field study was designed to provide an evaluation of the initial version of the VALMET model being developed by Pacific Northwest Laboratory.

The Brush Creek Valley is a narrow 650-m deep, near-linear valley having no major tributaries. The valley, which drains the Roan Plateau, is a main tributary to Roan Creek and is located approximately 50-60 km northeast of Grand Junction, Colorado. In the Brush Creek experiments, elevated continuous releases of SF_6 were made from a dual tethered balloon release system above the valley floor center, approximately 10 km up-valley from its confluence with Roan Creek. Releases were effected on three clear or partly cloudy mornings beginning at 0400-0500 local time from heights near 105 m. The releases were continued for 3 to 6 hours to determine how concentrations on the valley floor and sidewalls would change following sunrise during the temperature inversion breakup period.

SF_6 concentrations were detected down-valley from the release point using an array of radio-controlled bag samplers, a balloon-borne vertical SF_6 profiling system, and two portable gas chromatographs operated on one sidewall of the valley. One continuous real-time SF_6 monitor was operated on the valley floor and another onboard a research aircraft. The initial analyses of the experiments can be summarized as follows:

(a) The early morning plume was carried down Brush Creek by the nocturnal down-valley wind system. The plume was contained almost entirely in the lowest 250 m of the valley where the temperature inversion was strongest. The elevated plume roughly paralleled the valley floor, although it rose somewhat relative to the floor.

(b) Diffusion of the nocturnal plume during its down-valley travel was particularly marked in the vertical direction. This was probably caused by the strong vertical shear that developed in the shallow but strong down-valley flows within Brush Creek.

(c) The plume centerline was not carried down the center of the valley during its nocturnal travel, but was displaced towards the east sidewall of the northwest-southeast-oriented valley. This produced relatively high nocturnal concentrations on the east sidewall at elevations of 50-150 m.

(d) The plume centerline shifted across the valley to the west sidewall after sunrise, producing highest concentrations on the sunlit west sidewall at elevations of 50-150 m. The cross-valley shift of the plume centerline was caused by the strong differential heating of the two sidewalls.

(e) Decreases in SF_6 concentrations in the lower part of the valley occurred as SF_6 was advected up the west sidewall in upslope flows that developed within the growing convective boundary layer over the slope. Concentrations increased in the higher levels of the valley as the temperature inversion broke up and as upslope flows developed.

Further discussion of the meteorological interpretation of the tracer experiment data summarizing the physical processes responsible for the observed plume transport and diffusion will be presented at an AMS conference by Whiteman et al. (1984).

SECTION 3

AVAILABLE COMPLEX TERRAIN MODELING TECHNIQUES

In this section are briefly described the modeling techniques and algorithms that are currently available for regulatory use or which, as part of EPA efforts, are being currently evaluated for potential regulatory use. As a means of identifying candidate models, it seems logical to list those complex terrain dispersion models the EPA now uses, and those that were submitted for evaluation in response to the March 1980 Federal Register "Call for Models" notice. These models have also been statistically evaluated on common data bases as will be described in the next section. In addition, descriptions are included of the techniques being evaluated in the ongoing EPA Complex Terrain Model Development program and of the VALMET and MELSAR models also being developed for the EPA.

It is recognized that this list of models is not exhaustive since other complex terrain dispersion models are in various stages of development and availability. These range in complexity from relatively simple and computationally-efficient algorithms to comprehensive three-dimensional numerical grid models. However, since the theme of this assessment document was directed to EPA regulatory applications, the above guidelines were followed to provide an objective selection of candidate models for performance evaluation.

A refined guideline model has not been established by the EPA for complex terrain settings. Models presently used by the EPA as conservative screening techniques in complex terrain settings for conditions when plume heights can be expected to be below the maximum height of nearby terrain are Valley, COMPLEX I, and COMPLEX II. The EPA has also developed the model COMPLEX/PFM, which is still undergoing evaluation. The following complex terrain models were submitted from the modeling community for evaluation by the EPA in response to the Federal Register notice: RTDM, PLUME5, 4141, SHORTZ, and IMPACT.

All but one (IMPACT) of the above models are of the Gaussian plume type; that is, ground-level concentrations are calculated on the basis of distance from the plume centerline to ground surface according to Gaussian plume spread dispersion statistics. These models differ, however, in parameterization of dispersion, the way wind speeds are used, the assumptions about plume trajectories, and in other parameterizations. A summary description of the COMPLEX I, COMPLEX II, and COMPLEX/PFM is given in this section followed by a brief discussion of how the other models differ from these.

In all cases, the reader is referred to the appropriate documentation for more complete information on each of these models. Since the Complex Terrain Dispersion Model, now undergoing development for the EPA, is significantly more complex than the other Gaussian type models, a detailed description is provided to allow a more complete understanding of the algorithms involved.

VALLEY MODEL

The Valley Model (Burt, 1977) is recommended by the EPA as the initial screen in a two-tiered screening approach for complex terrain analyses in support of regulatory decisions. Valley is designed to provide an estimate of the maximum 24-hour pollutant concentration expected to occur on elevated terrain near a point source of air pollution in any 1-year period. This concentration is computed with a steady-state, univariate Gaussian plume dispersion equation, modified to provide a uniform crosswind distribution over a 22.5° sector and using assumed worst-case meteorological conditions.

The model assumes that the plume travels toward nearby terrain with no vertical deflection until the centerline of the plume comes to within 10 m of the local terrain surface. Thereafter, the centerline is deflected to maintain a stand-off distance of 10 m from the terrain surface. The plume is considered to impinge upon the terrain at points where terrain height equals the plume height, and the impingement point used in the calculation of maximum plume impact is the nearest such topographic point as viewed from the source.

Worst-case meteorological conditions are defined by that combination of wind speed and Pasquill-Gifford dispersion stability class that produces the highest possible concentration at the impingement point. For large sources of air pollution, a stack-top wind speed of 2.5 m/s and Pasquill-Gifford stability class F are recommended as those conditions that will produce the highest concentrations during stable conditions when plume impingement is most likely. The model estimate is implied to be a 1-hour average concentration. The 24-hour average concentration is estimated by dividing this 1-hour average concentration by four, on the premise that the impinging plume may affect a specific point for no more than 6 hours in any 24-hour period.

COMPLEX I, COMPLEX II, AND COMPLEX/PFM MODELS

The COMPLEX I (EPA, 1981a) and COMPLEX II (EPA, 1981b) models are multiple point source sequential terrain models formulated by the Complex Terrain Team at the EPA Workshop on Air Quality Models held in Chicago in February 1980. COMPLEX I is a univariate Gaussian horizontal sector-averaging model (sector width = 22.5°), while COMPLEX II computes off-plume-centerline concentrations according to a bivariate Gaussian distribution function. Both models are very closely related to the MPTER model in both structure and operation. Anyone who is not familiar with either COMPLEX or MPTER should consult the MPTER user's manual (Pierce and Turner, 1980) and the analysis report on COMPLEX I and COMPLEX II (Irwin and Turner, 1983).

Terrain treatment in the COMPLEX models varies with stability class. Neutral and unstable classes use a 0.5 terrain adjustment, while stable classes use no terrain adjustment when the recommended options are selected. With 22.5° sector averaging, COMPLEX I, when used in the regulatory mode, performs sequential Valley plume impingement calculations for stable cases. COMPLEX II plume impingement calculations are similar, with the exception that sector averaging is not used.

The COMPLEX/PFM model (Strimaitis et al., 1983) is a modified version of COMPLEX I and II that contains a Potential Flow Module (PFM). COMPLEX/PFM has the ability to utilize potential flow theory calculations for neutral to moderately stable flows. The PFM option invokes either COMPLEX I, COMPLEX II, or PFM computations depending upon the stability class and the Froude number. Unlike previous versions, however, all sources must be located at the same point.

The PFM option enhances the ability of COMPLEX to perform complex terrain Gaussian plume dispersion computations in two important areas. First, it incorporates plume deflections and distortions through streamline computations derived from potential flow theory. This enhancement approximates at least first-order terrain effects on plume geometry. And, because the streamline computations vary with obstacle shape, plume height, and Froude number, plume distortions are coupled directly to meteorological variations and the approximate terrain geometry in a way that no single terrain adjustment could be. Second, the use of the PFM option requires vertical temperature and wind velocity information to characterize the Froude number, the dividing-streamline height, and stable plume rise. Availability of the Froude number and the dividing-streamline height removes the assumption of coupling between the surface dispersion stability class and the dynamics of the flow aloft at plume elevation under stable conditions. It is not necessary to identify plume impingement with class E or F dispersion conditions.

COMPLEX II is invoked by COMPLEX/PFM whenever the stability class is either 1, 2, or 3 (A, B, or C), regardless of the Froude number. In these cases plume growth is rapid and the details of terrain adjustment are not so important. PFM is always invoked for stability class 4(D), and is invoked for stability classes 5(E) and 6(F) whenever the flow along the plume streamline has enough kinetic energy to rise against the stable density gradient and surmount the highest terrain elevation along the wind direction. Such a plume is considered to be above the dividing streamline of the flow.

COMPLEX I is invoked by COMPLEX/PFM whenever the plume is found to be beneath the dividing streamline of the flow (classes 5 and 6). Plumes beneath the dividing streamline no longer pass over the terrain peak and therefore may impinge on the face of the hill. Thus, when used in the regulatory mode, the PFM option defaults to Valley-like computations for impingement cases.

ROUGH TERRAIN DIFFUSION MODEL

The Rough Terrain Diffusion Model (RTDM) is a sequential Gaussian plume model designed to estimate ground-level concentrations in rough (or flat) terrain in the vicinity of one or more co-located point sources (ERT, 1982). Off-plume-centerline concentrations are computed according to a bivariate Gaussian distribution function. Only buoyancy-dominated sources should be modeled with RTDM because momentum effects on the plume are ignored.

Rather than assuming full reflection (Valley-like computations) for cases of plume impingement, RTDM uses a partial plume reflection algorithm that takes into account the second law of thermodynamics and estimates a maximum effect of reflection (which is less than full reflection) for a plume approaching a terrain slope.

In stable conditions, the dividing-streamline height (H_c) is computed from the wind speed, the terrain height, and the strength of the inversion. Plumes below this height are allowed to impinge on the terrain. During neutral and unstable conditions or above H_c in stable conditions, a "half-height" correction simulates the effect of terrain-induced plume modifications on ground-level concentrations.

Rather than using Pasquill-Gifford stability classes, RTDM uses on-site turbulence intensity data (i_y, i_z) to estimate horizontal and vertical ambient dispersion. Horizontal wind shear data can be used to make refined estimates of the horizontal extent of the plume.

PLUME5 MODEL

PLUME5 is a multiple source, steady-state Gaussian plume dispersion model designed for point source applications (Hsiung and Case, 1981). This model is closely related to the CRSTER model in both structure and operation. Off-plume centerline concentrations are computed according to a bivariate Gaussian distribution function. The treatment of terrain by PLUME5 uses Briggs final plume rise algorithm with the determination of stable layer penetration dependent on plume height:

(a) When the final plume height is above the stable layer, concentration estimates are calculated only for those receptors at or above the stable layer top.

(b) When the plume height lies within the stable layer, concentration estimates are calculated only for those receptors located within the stable layer.

(c) When the plume height (H) falls below the stable layer and the receptor lies above the stable layer base, then the concentration is set to zero. If the receptor height (Z) is below the stable layer base, the receptor height is redefined as follows:
   - If $Z < H/2$, then the terrain height is not modified.
   - If $Z \geq H/2$, then a conservative modification to the one-half plume height correction is used.

   PLUME5 performs Valley-like calculations for stable cases with plume impaction.

PLUME5 uses stability categories as determined from on-site horizontal turbulence intensity data (σ_θ), on-site vertical temperature gradients, or Pasquill's stability classification scheme. Pasquill-Gifford-Turner dispersion coefficients are used for each stability category. Stability classes A-F are utilized with stability class G assigned to class F. An option is available to treat stability class A as class B. Enhanced horizontal dispersion due to vertical wind directional shear may be employed.

4141 MODEL

Model 4141 (ENVIROPLAN, 1981) is a modified version of the bivariate Gaussian distribution CRSTER model. The modifications include the location of the plume centerline above ground level in complex terrain, stability classification, dispersion-rate calculations as a function of the stability class, and the minimum approach of the plume centerline to the ground.

The 4141 model uses Turner stability categories with class G treated as class F, and Pasquill-Gifford dispersion rates including buoyancy-induced dispersion. The horizontal dispersion rates are 1.82 times the original Pasquill-Gifford dispersion rates, which accounts for differences in sampling times.

The effective stack height is reduced by half of the increase in ground elevation above stack base for unstable and neutral conditions (half-height) and by 0.75 of the increase in ground elevations above stack base for stable conditions (quarter-height). The CRSTER-like minimum terrain approach of plume centerline is eliminated although, through the use of the quarter-height correction, there are no pure cases of impingement. Valley-like calculations in effect occur whenever the plume is close to impinging on the terrain feature.

SHORTZ MODEL

SHORTZ is a bivariate Gaussian dispersion model designed to calculate average ground-level concentrations produced by emissions from multiple stack, building, and area sources (Bjorklund and Bowers, 1979). The steady-state Gaussian plume equation for a continuous source is used to calculate ground-level concentrations.

Rather than using Pasquill-Gifford-Turner σ's, vertical and lateral plume dimensions are calculated by using on-site turbulent intensities (i_y, i_z) in simple power law expressions that include the effects of the initial source dimension. Techniques for enhancing horizontal dispersion due to vertical wind direction shear and for including buoyancy-induced dispersion are used.

When SHORTZ is applied in complex terrain, the plume axis is assumed to remain at the plume stabilization height and the plume is allowed to mix to the ground as long as the stabilization height is within the surface mixing layer. An effective mixing height is defined to be terrain-following in order to prevent a physically unrealistic compression of plumes as they pass over elevated terrain. SHORTZ performs Valley-like calculations for impingement cases.

INTEGRATED MODEL FOR PLUMES AND ATMOSPHERICS IN COMPLEX TERRAIN

The Integrated Model for Plumes and Atmospherics in Complex Terrain (IMPACT) is a three-dimensional grid model used to calculate the impact of either inert or reactive pollutants, in simple or complex terrain, emitted from either point or area sources (Tran et al., 1979). Unlike Gaussian-type models, IMPACT determines concentrations as a function of advection, diffusion, source, and chemistry. This formulation allows for the treatment of single, multiple point or area sources, the effects of arbitrary vertical temperature stratifications, shear flows caused by atmospheric boundary layers or by terrain effects, terrain channeling, and chemical transformations.

The method of calculating diffusivities from the DEPICT model using empirical formulations is used. The vertical diffusivity,

$$D_V = .45\ u\sigma_\varepsilon \ell, \tag{8}$$

is a function of the windspeed (u), the standard deviation of the wind vane fluctuation (σ_ε), and the turbulence length scale (ℓ). σ_ε is empirically related to stability and ℓ is empirically related to height and stability. The horizontal diffusivity is then calculated using the following formulation,

$$D_H = \alpha D_V, \tag{9}$$

where α is empirically related to stability.

Wind fields are objectively-determined, non-divergent flow fields based on local data. The plume rise and terrain impaction are controlled by the wind and diffusivity fields. The Briggs layered plume rise algorithm including the penetration of stable layers is used.

COMPLEX TERRAIN DISPERSION MODEL

As part of the EPA Complex Terrain Model Development program, Environmental Research and Technology, Inc. (ERT) has produced the Complex

Terrain Dispersion Model (CTDM). In its current stage of ongoing development, the CTDM is a point source plume model that incorporates several concepts about stratified flow and dispersion over an isolated hill. A central feature of CTDM is its use of the dividing-streamline height (H_c) to separate the flow into two discrete layers. This basic concept was suggested by theoretical arguments of Drazin (1961) and Sheppard (1956), and was demonstrated through laboratory experiments by Riley et al. (1976), Brighton (1978), Hunt and Snyder (1980), Snyder et al. (1980), and Snyder and Hunt (1984). The flow below H_c is constrained to move in horizontal planes, allowing no motion in the vertical. Consequently, plume material below H_c travels along and around the terrain, rather than up and over the terrain. The flow above H_c is allowed to rise up and over the terrain. Two separate components of CTDM compute ground-level concentrations resulting from material in each of these flow regimes. LIFT simulates the flow above H_c and WRAP handles the flow below H_c.

The LIFT Component

The flow above H_c is considered to be weakly stratified. That is, the stratification is strong enough to influence the flow pattern (e.g., lee waves) and the diffusion, but not strong enough to inhibit significant vertical motions. To simplify the modeling task, H_c is assumed to be a level surface, and the flow above H_c "sees" only that portion of the hill that lies above H_c.

A fluid modeling study was performed by Snyder and Lawson (1983) at the EPA Fluid Modeling Facility to assess the utility of this approximation. The results of this study confirmed that this approximation is reasonable with regard to estimating the locations and values of maximum ground-level concentrations and areas of coverage on the windward side of the hill. Poorer correspondence was found in the lee of the hill for plumes released well above H_c, and this is apparently due to lee-wave effects.

The plume is allowed to develop as if the terrain were perfectly flat until it reaches the point where the H_c surface intersects the hill (at x =

s_o, see Figure 3). If H_c is zero, then this zone extends from the source to the base of the hill, although it could conceptually extend to any point where the hill is thought to exert a significant influence on the flow. Beyond s_o, the plume material below H_c is disregarded by the LIFT component, and the evolution of the remaining material is modeled as if the terrain were flat and the lower boundary were H_c (with full reflection). However, the wind speed, plume height above H_c, plume spread, and lateral position of the plume centerline relative to the receptor are all modified to reflect the net alteration of these properties between s_o and s (the distance to the receptor) induced by the presence of the hill. The simplicity of the Gaussian plume solution is retained in this way, while the full dilution of the plume from the source to the hill (s_o) as well as the effects of the hill on both flow and dispersion beyond s_o are explicitly incorporated.

Aside from the obvious distinction of incorporating the primary influence of H_c on the plume-terrain interaction, this approach differs notably from the current regulatory modeling approach (at least as embodied in COMPLEX I and II) in that the terrain influence only affects the plume once it is over the terrain. The "partial height" modeling approach of COMPLEX and similar models actually "lowers" the plume at the source. If this technique were engineered to produce the "correct" hill-influenced ground-level concentrations, the partial height factor would need to be a function of downwind distance, terrain shape, and distance between source and terrain. As employed in regulatory modeling, however, the partial height factor depends only on the stability class and the heights of the source and receptor, so that its use has led to problems of interpreting "surface reflection" from sloping terrain, as well as to problems in justifying values chosen for the partial height factor.

Terrain-induced modifications to the plume arise from the distortion of the flow over the hill. A streamline of the flow will be deflected to the side (unless it lies in a plane of symmetry) and will pass closer to the hill surface. Adjacent streamlines are deflected in much the same way, but are generally displaced by differing amounts, which in turn changes the spacing between streamlines and hence causes changes in the local speed of the flow. As a result, the plume trajectory is curved, the time of travel does not vary linearly with distance, the plume distorts so that it is thinner in the

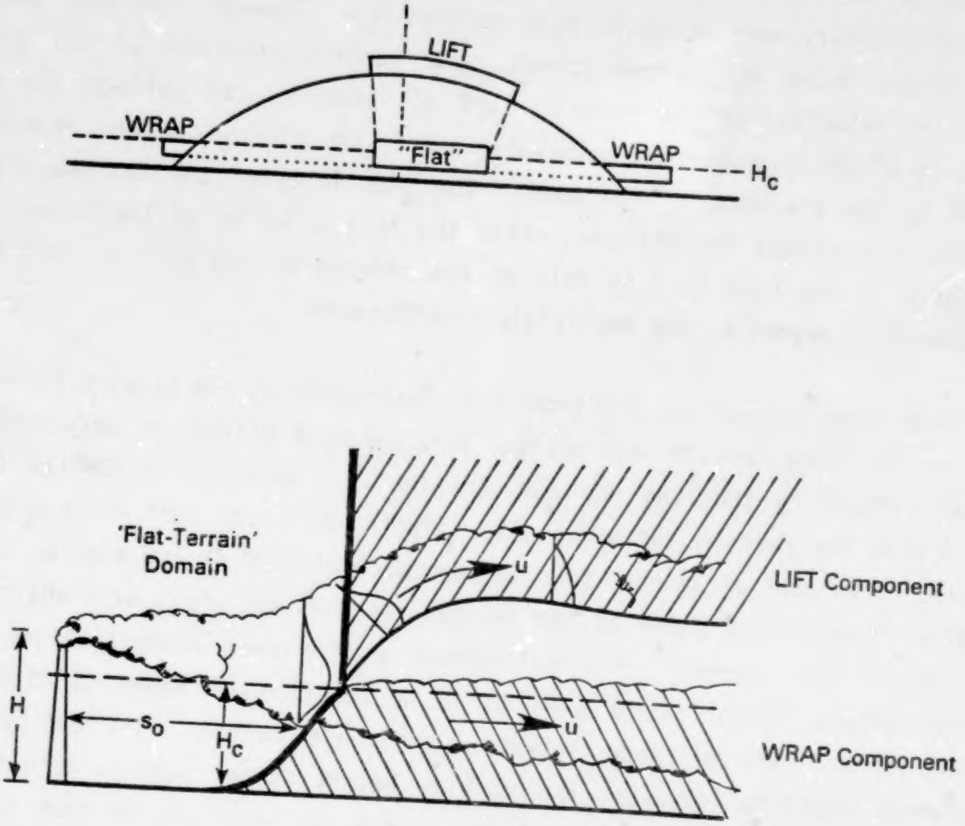
LIFT
WRAP
"Flat"
WRAP
H_c
'Flat-Terrain' Domain
u
LIFT Component
H
s_o
H_c
u
WRAP Component

Figure 3. Idealized stratified flow about hills indicating domains of individual CTDM component algorithms. The s_o dimension is the distance from the source to the intersection of H_c with the hill surface for the LIFT domain, and from the source to the terrain contour equal in height to the receptor elevation for the WRAP domain.

vertical direction and wider in the lateral direction, and the turbulence statistics vary. In addition, as shown by Hunt and Mulhearn (1973), turbulent diffusion across streamlines is enhanced by the contraction of the distance between streamlines in the vertical direction, and is retarded by the expansion of the distance between streamlines in the lateral direction.

Hunt and Mulhearn explicitly track these changes through the use of line integrals along the streamline that coincides with the plume centerline. The LIFT component has been designed to take average values of the changes in flow properties over the interval between s_o and s. These average values then guide the distortion applied to the concentration distribution at s_o and the flow speed used in the ensuing calculation. In essence, LIFT distorts the plume at s_o by an amount representative of the actual distortion in the flow between s_o and s, and then a flat terrain computation is used to estimate the effect of these distortions on the diffusion of material to the surface over the interval $s-s_o$. Hence, a continuous process is represented by a two-step process in which the distortion of the flow and the diffusion of the plume in the distorted flow are treated successively. This approach, while not as rigorous as the Hunt and Mulhearn approach, allows development of a modeling framework in which the terrain effects appear as simple factors within the flat terrain solution.

Quantities in the distorted flow are related to quantities of the undistorted flow by means of terrain factors. These factors are local in the sense that they depend on the position of the receptor on the terrain, even though they represent the average terrain effect on the flow from s_o to s. T_h and T_ℓ are factors that specify the amount of streamline distortion in the vertical and lateral directions; T_u specifies the resultant change in the flow speed; and $T_{\sigma z}$ and $T_{\sigma y}$ specify changes in the diffusivity in the vertical and lateral directions.

The factor T_h accounts for the effective contraction of the distance between streamlines in the vertical. A simple model for the change in streamline spacing applies a constant depression factor to all streamlines over a particular location on the terrain. But note that the perturbation caused by a hill should decrease with height, so that this simple model must be viewed as an approximation to be applied at plume centerline height. Similarly, T_ℓ is evaluated for a particular plume path.

The speed factor, T_u, is obtained by conserving mass. The condition $T_u T_h T_\ell = 1$ must be maintained at every point in the flow. The factor T_σ (denoting either $T_{\sigma z}$ or $T_{\sigma y}$) should account for the effective diffusivity between s and s_o. In the present form of CTDM, the magnitudes of these terrain effect factors are scaled from potential flow calculations.

The concentration on the hill surface at the point (s,ℓ) is then given by

$$C(s,\ell) = \frac{Qe^{-0.5\left(\frac{\ell/T_\ell - L}{\sigma_{ye}}\right)^2}}{2\pi\sigma_{ye}\sigma_{ze}u}\left[e^{-0.5\left(\frac{H_s-H_c}{\sigma_{ze}}\right)^2}\left(1-\mathrm{erf}\left(\frac{H_c-H_s}{\sqrt{2}\sigma_{ze}}\;\frac{\sigma_z^*/T_z}{\sigma_{ze}}\right)\right)\right.$$

$$\left.+\;e^{-0.5\left(\frac{H_s+H_c}{\sigma_{ze}}\right)^2}\left(1-\mathrm{erf}\left(\frac{H_c+H_s}{\sqrt{2}\sigma_{ze}}\;\frac{\sigma_z^*/T_z}{\sigma_{ze}}\right)\right)\right] \quad (10)$$

where $T_z = T_h/T_{\sigma z}$, $T_y = T_\ell/T_{\sigma y}$, and the source is located at $(0, L, H_s)$. The terrain-induced modifications are easier to observe if H_c is set to zero:

$$C(s,\ell) = \frac{Qe^{-0.5\left(\frac{\ell/T_\ell - L}{\sigma_{ye}}\right)^2}}{\pi\sigma_{ye}\sigma_{ze}u}\; e^{-0.5\,(H_s/\sigma_{ze})^2}. \quad (11)$$

The effective plume size (subscripted by e) is given by

$$\sigma_{ze}{}^2 = \sigma_z{}^2(s_o) + \sigma_z^{*2}/T_z{}^2 \quad (12)$$

$$\sigma_{ye}{}^2 = \sigma_y{}^2(s_o) + \sigma_y^{*2}/T_y{}^2 \quad (13)$$

where

$$\sigma^{*2} = \sigma^2(s) - \sigma^2(s_o). \quad (14)$$

If T_z and T_y are not equal to unity, the effective size of the plume differs from the unmodified plume and the effective lateral distance from the plume centerline to the receptor is altered. For illustration, let L = 0. Then if $T_\ell > 1$, which is generally the case because the streamlines are deflected to the side to some degree, the apparent receptor location (ℓ/T_ℓ) lies nearer the plume centerline. Aside from this lateral shift in the impact region on the terrain, the influence of the terrain is exhibited only through changes in the rate of effective plume growth. When T_z is less than unity (again, this is generally the case), σ_{ze} exceeds σ_z at s and so more plume material may lie "nearer" the surface. Furthermore, because T_y is generally greater than unity, σ_{ye} is less than σ_y at s, so the plume is not fully diluted by the increase in σ_{ze}. As a consequence, Equation 10 may estimate ground-level concentrations in excess of flat terrain estimates even when H_c is zero.

If H_c is nonzero, but less than H_s, Equation 10 will estimate even greater ground-level concentrations because the flow over the depth H_c beneath the plume is "removed," allowing the less dilute portion of the plume to approach nearer the surface. In particular, if $H_c = H_s$, then Equation 10 places the centerline concentration at ground level, producing a centerline "impingement" result.

In the use of Equation 10, the terrain factors should be regarded as local terrain effects factors for a particular receptor. The degree of flow deformation depends on whether the flow must go directly over the crest, or pass to one side in approaching the receptor. Once the local factors are obtained, they are applied to the entire plume.

If there should be a good deal of meander over the averaging period for the model computation, it is not apparent that Equation 10 is appropriate. Therefore, consider Equation 10 appropriate for a "filament" plume. The "filament" plume is defined to be a plume described by the flow field statistics obtained for a sampling period commensurate with the time of travel from the source to the hill. The mean concentration at a receptor for an averaging period greater than the time of travel is a weighted average of many "filament" plumes:

$$C_m = \int_{-\infty}^{+\infty} C(s,\ell \mid \theta_i)\ P(\theta_i)\ d\theta_i . \qquad (15)$$

$P(\theta)$ is the probability that the wind is from the θ direction during the averaging period, and $C\ (s,\ell \mid \theta)$ is the concentration resulting from a "filament" plume from direction θ. For a distribution of wind directions that has a single dominant mode at θ_m, $P(\theta)$ may be approximated by a Gaussian distribution:

$$P(\theta) = \frac{e^{-0.5\left(\frac{(\theta-\theta_m)s}{\sigma_{ym}}\right)^2}}{\sqrt{2\pi}\ \sigma_{ym}/s} . \qquad (16)$$

Using a similar arc-length notation for lateral distance, $C\ (s,\ell \mid \theta)$ may be written as

$$C(s,\theta_r \mid \theta) = \frac{F_z(\theta)}{\sigma_{ye}}\ e^{-0.5\left(\frac{(\theta_r-\theta)s}{\sigma_{ye}}\right)^2} \qquad (17)$$

where $F_z(\theta)$ denotes the vertical distribution portion of Equation 10, and θ_r is the direction from the apparent or effective receptor location to the source.

By assuming that the "filament" plume is narrow, set $F_z(\theta)$ to $F_z(\theta_r)$, and evaluate σ_{ye} for a plume from θ_r. This makes explicit the use of the terrain factors that are local to the receptor. The solution of the integral gives

$$C_m = \frac{F_z(\theta_r)}{\sigma_{yT}}\ e^{-0.5\left(\frac{(\theta_r-\theta_m)s}{\sigma_{yT}}\right)^2} \qquad (18)$$

where

$$\sigma_{yT}^2 = \sigma_{ym}^2 + \sigma_{ye}^2 . \qquad (19)$$

Because σ_{ym} is viewed as the statistic for just the meander component of the wind fluctuations over the averaging period, and σ_{ye} is viewed as the measure (including the terrain modification) of the mean "filament" plume spread, $\sigma_{yT} = \sigma_{ye}$ in the absence of meander, and Equation 10 is obtained once again.

The WRAP Component

The flow below H_c is considered to be completely two-dimensional, allowing no motion in the vertical. Consequently, the flow must pass to one side or the other of the hill, and the one streamline that actually touches and passes round both sides of the hill, separates the two flows and is termed the stagnation streamline (Figure 4). The flow on either side of the stagnation streamline undergoes distortion such that a streamline in the flow is deflected to the side, but passes closer to the hill surface than its initial distance from the stagnation streamline. Adjacent streamlines are displaced by differing amounts, which in turn changes the horizontal spacing between streamlines, and hence causes changes in the local speed of the flow. The effect of these distortions on ground-level concentrations is not unlike those formulated in LIFT for flow over a two-dimensional hill, wherein $T_{\ell} = 0$.

The primary difference between the WRAP and LIFT formulations arises from the location of solid boundaries and the relationship between the position of these boundaries and the wind direction fluctuations. The terrain effect is modeled in WRAP by re-initializing the flow at s_o. Note that receptors below H_c experience an s_o different from that for receptors above H_c (Figure 3). Below H_c, s_o is the distance along the stagnation streamline to the terrain contour equal in height to the receptor elevation. The concentration at a receptor downwind of s_o is composed of concentrations from that part of the concentration distribution at s_o that lies below H_c, and that also lies on the same side of the stagnation streamline as the receptor. Reflection of plume material is allowed from the plane $z = 0$ over the entire distance s, and reflection is also allowed from the "stagnation streamline" beyond s_o. Note that the stagnation streamline forms the boundary of the hill surface in horizontal cross section.

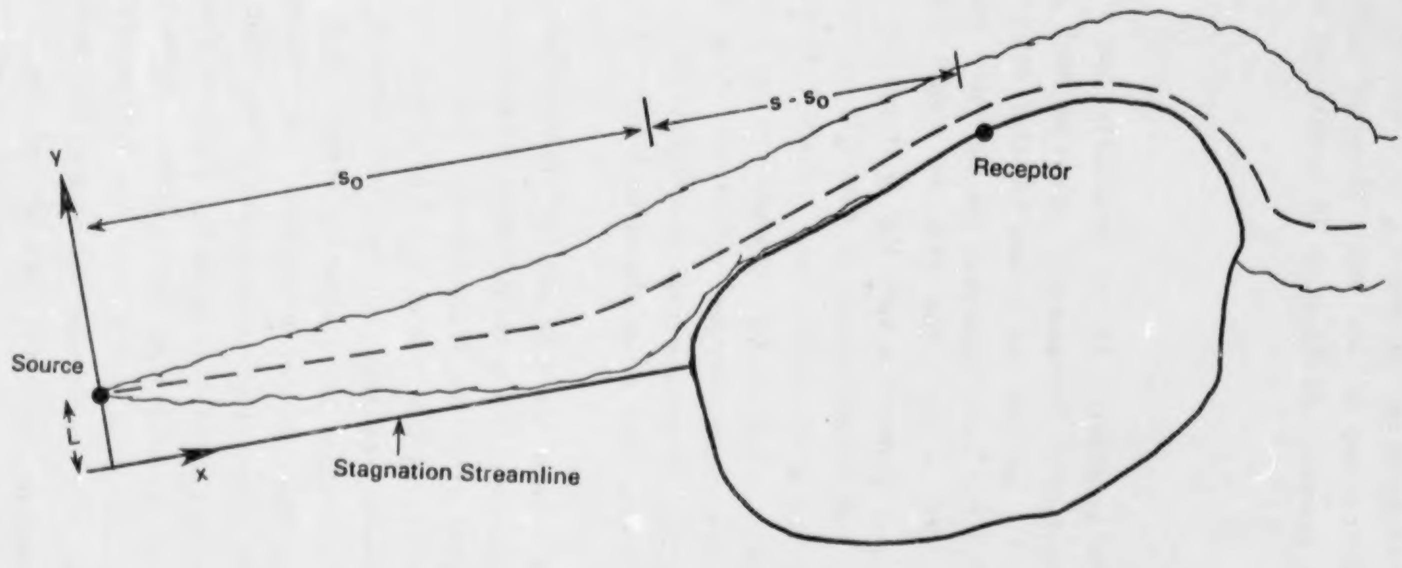
y
s_o
$s - s_o$
Receptor
Source
L
x
Stagnation Streamline

Figure 4. Plan view of plume in two-dimensional flow around a hill.

The terrain influences are incorporated by deforming the source distribution at s_o, and by altering the flow in which the source elements diffuse. For a receptor located on the hillside at a distance s and a height H_r, the concentration due to a source located at (0, L, H_s) contains contributions from those elements below H_c, and on the same side of the stagnation streamline as L.

Noting that $T_h = 1$ for this two-dimensional flow, the concentration is given by

$$C(s,0,H_r) = \frac{Q}{4\pi u \sigma_{ye} \sigma_{ze}} e^{-0.5\left(\frac{L}{\sigma_{ye}}\right)^2} \left(1 + \mathrm{sign}(y_e)\ \mathrm{erf}\left(\frac{L\sigma_y^*/T_y}{\sqrt{2}\sigma_{yo}\sigma_{ye}}\right)\right)$$

$$\cdot \left(B_1 e^{-0.5\left(\frac{H_s - h}{\sigma_{ze}}\right)^2} + B_2 e^{-0.5\left(\frac{H_s + h}{\sigma_{ze}}\right)^2}\right). \qquad (20)$$

Most of the notation here has already been encountered in the description of the LIFT component. The factor sign(y_e) denotes the sign of the receptor position in the coordinate system with x-axis aligned with the flow, and it results from the choice of integrating over the "positive" or "negative" portion of the flow. The factors B_1 and B_2 are given by

$$B_1 = \mathrm{erf}\left(\frac{b_1 - b_2 - b_3}{b_o}\right) + \mathrm{erf}\left(\frac{b_1 + b_2 + b_3}{b_o}\right) \qquad (21)$$

$$B_2 = \mathrm{erf}\left(\frac{b_1 - b_2 + b_3}{b_o}\right) + \mathrm{erf}\left(\frac{b_1 + b_2 - b_3}{b_o}\right) \qquad (22)$$

where

$$\begin{aligned} b_0 &= \sqrt{2}\ \sigma_{ze}\ \sigma_{zo}\ \sigma_z^* \\ b_1 &= T_z\ H_c\ \sigma_{ze}{}^2 \\ b_2 &= h\ \sigma_{zo}{}^2/T_{\sigma z} \\ b_3 &= H_s\ \sigma_z^{*2}/T_z. \end{aligned} \qquad (23)$$

The concentration estimate from Equation 20 is quite sensitive to the wind direction. The wind direction determines the stagnation streamline, and this in turn prescribes the relative position of both the source and the receptor in the undistorted flow through the quantities s, s_0, and L (Figure 4). Because the terrain effects are characterized through factors that are local in the context discussed previously, they also depend on s, s_0, and L. Therefore, the notion of a "filament" plume is implicit in the foregoing development, as it was in the development of the LIFT component.

If the distribution of wind directions over the averaging time is highly non-Gaussian, then the mean concentration is probably best estimated by simulating a sequence of "filament" plumes. However, for distributions closer in shape to the Gaussian distribution, an expression in the form of Equation 15 may be used with the Gaussian distribution specified in Equation 16.

Integrating Equation 20 within Equation 15 to obtain the mean concentration C_m is simplified if we expect the "filament" plume to be narrow so that concentrations for wind directions much different from the stagnation streamline orientation θ_s through the source (and therefore θ_r as well) are insignificant. In that case, s and s_0 may be treated as constants, and L can be represented by the small-angle approximation so that

$$C_m = \frac{F_z(\theta_s)s}{\sqrt{2}\pi\sigma_{ye}\sigma_{ym}} \int_{-\infty}^{+\infty} e^{-0.5\left(\frac{(\theta-\theta_m)s}{\sigma_{ym}}\right)^2} e^{-0.5\left(\frac{(\theta-\theta_s)r}{\sigma_{ye}}\right)^2}$$

$$\cdot \left(1 + \mathrm{sign}(y_e)\ \mathrm{erf}\frac{(\theta-\theta_s)r\ \sigma_y^*/T_y}{\sqrt{2}\ \sigma_{yo}\sigma_{ye}}\right)d\theta. \qquad (24)$$

The solution of this integral is obtained by approximating the error function with a two-section piecewise linear curve.

Formulation of σ_z

The formulation of σ_z in CTDM is based on the well-accepted behavior described by

$$\sigma_z = \sigma_w t \quad ; \quad t << T_L \tag{25}$$

$$\sigma_z = (2K_z t)^{0.5} \quad ; \quad t >> T_L. \tag{26}$$

In Equations 25 and 26, σ_w is the standard deviation of vertical velocity fluctuations, t is the travel time from the source, T_L is the dispersion time scale, and K_z is the eddy diffusivity defined by

$$K_z \equiv \sigma_w \ell \text{ , where } \ell = \sigma_w T_L. \tag{27}$$

In a stably stratified flow, a fluid element must overcome a stable potential temperature gradient in order to be displaced vertically. Simple energy arguments suggest that this gradient imposes a length scale of the order of σ_w/N on vertical motion, where N is the Brunt-Vaisala frequency. Consequently, the mixing length ℓ_s is proportional to this length scale so that

$$\ell_s = \gamma^2 \sigma_w/N \tag{28}$$

where γ is an undetermined constant.

Surface-layer relationships (Businger, 1973) in the limit of z-less stratification are employed to estimate γ.

Assuming that $K_H = K_z$, we find that

$$\gamma^2 = \frac{1}{\sqrt{\beta}\, a^2}. \tag{29}$$

With $\beta = 4.7$ and $a = 1.3$, γ equals 0.52. Note that when N is small, ℓ_s can become very large, and it becomes necessary to consider the effect of the ground on limiting the length scale. In the absence of stratification, one expects the mixing length to scale with height, so

$$\ell_n = \alpha H_s \tag{30}$$

where the subscript n is used to distinguish the neutral length scale ℓ_n from the stable scale ℓ_s.

Surface-layer relationships indicate that

$$\alpha = k/a\Phi_H(0). \tag{31}$$

If the values of $k = 0.35$ and $\Phi_H(0) = 0.74$ (Businger, 1973) are used, α equals 0.36.

Interpolation between ℓ_n and ℓ_s is accomplished with the following formulation for ℓ

$$1/\ell = 1/\ell_s + 1/\ell_n. \tag{32}$$

Equation 32 has been used by other investigators (see Hunt et al., 1983 for example). Then the dispersion time scale is given by

$$T_L = \ell/\sigma_w. \tag{33}$$

The σ_z formulation, which interpolates between the linear and square-root growth rates, is one used by other authors (Deardorff and Willis, 1975):

$$\sigma_z = \sigma_w t/(1 + t/2T_L)^{\frac{1}{2}}. \tag{34}$$

Formulation of σ_y

Past versions of CTDM have estimated σ_y by assuming that the transverse spread of the plume grows linearly with time. This implies that the Lagrangian time scale for the transverse spectrum is long compared to the time of travel to the hill. While this may be the case for many of the Cinder Cone Butte experiments, there are some experiment hours in which the linear growth law appears to overestimate the dilution of the plume. This was deduced from comparisons of observed ground-level SF_6 concentrations with estimates of the plume "centerline" concentrations.

The Lagrangian time scale can be incorporated into the expression for σ_y by means of the interpolation contained in the σ_z formulation:

$$\sigma_y = i_y s \left(1 + \frac{s}{2uT_{LT}}\right)^{\frac{1}{2}} . \tag{35}$$

The Lagrangian time scale for the transverse spectrum T_{LT} cannot be estimated from the flow properties, but it may be estimated from the turbulence measurements. Pasquill and Smith (1983) point out that if the turbulence is assumed to be isotropic, and if the longitudinal correlogram is modeled by an exponential with an Eulerian time scale of T_E, then

$$\frac{(\sigma_{\tau,o})^2}{(\sigma_{\infty,o})^2} = 1 - \frac{T_E}{\tau}\left(1 - e^{-\tau/T_E}\right) \tag{36}$$

gives the relationship between the crosswind turbulence measured over a time τ to that measured for an infinite sampling time. Because we have measured i_y (5 min) and i_y (60 min), we can solve for T_E. Then the Lagrangian time scale for the transverse spectrum is approximately equal to

$$T_{LT} = 0.5\ T_L = 0.5\ T_E\ (0.68/i_{y\infty}) \tag{37}$$

where

$$i^2_{y\infty} = \frac{i^2_y\ (5\ \text{min})}{1 - \frac{T_E}{300}\left(1 - e^{-300/T_E}\right)} . \tag{38}$$

VALMET AND MELSAR MODELS

In addition to the Complex Terrain Model Development program, the EPA is also conducting the Green River Ambient Model Assessment program. The objective of this latter program is to develop site-specific air quality models for complex terrain of the type found in the Green River Oil Shale Formation in Wyoming, Utah, and Colorado. Principal problems are transport and diffusion from single sources in deep valleys and regional effects of all sources. The VALMET and MELSAR models are being developed by Pacific

Northwest Laboratory to be used for these respective problems. Neither of these models has been fully evaluated with field data, although an evaluation of VALMET is underway. A review of the overall program is given by Schiermeier et al. (1983a) and descriptions of VALMET and MELSAR are given by Whiteman and Allwine (1983) and Allwine and Whiteman (1984), respectively.

The VALMET (Valley Meteorology) model is intended for use primarily for the morning fumigation period in deep valleys, where upslope flows generated by solar heating cause polluted air at mid-valley to descend to the ground. The fundamental physical mechanism is discussed by Whiteman and McKee (1977, 1982), who conducted numerous meteorological studies of the structure of winds and temperatures in Colorado mountain valleys. They observed that the mid-valley inversion descended in the early morning as mass lost in upslope flows was replaced by air above the valley floor. They developed an Eulerian grid model to simulate the observed phenomena, and included the differential solar heating of the valley walls. In their later work for the EPA, they added an air pollution concentration field to the model, beginning with a stable Gaussian plume oriented along the valley axis before sunrise. The Eulerian grid model then accounted for fumigation after sunrise.

Two field experiments have been conducted in the Green River oil shale region in 1980 and 1982, including meteorological observations and SF_6 tracer data. Analysis of these data and evaluation of VALMET are currently underway (Whiteman et al., 1984).

The MELSAR (Mesoscale Location-Specific Air Resources) model is a puff-trajectory model suitable for calculating transport and dispersion over a 500-km by 500-km region, including the effects of underlying complex terrain. The flow module is a three-dimensional, mass-consistent flow model using a terrain-following coordinate system (Drake et al., 1981). Pollutant concentrations are described in a Gaussian fashion about a puff center of mass, where continuous sources are approximated by puff release rates of one per hour. The model has not yet been tested with observations.

SECTION 4

RESULTS OF MODEL EVALUATION STUDIES

A number of model evaluation studies performed over the past few years have focused on the application of dispersion models to complex terrain settings. The discussion here attempts to draw out some of the more important findings and suggestions for appropriate modeling techniques that have emerged from two of these efforts.

TRC EVALUATION OF COMPLEX TERRAIN DISPERSION MODELS

This study (Wackter and Londergan, 1984) was sponsored by the EPA Office of Air Quality Planning and Standards, and was performed by TRC Environmental Consultants, Inc., using statistical measures recommended by the American Meteorological Society (Fox, 1981). Two field measurement data bases were used for testing: the Cinder Cone Butte (CCB) tracer data base resulting from the first field experiment of the EPA Complex Terrain Model Development program and the Westvaco Luke Mill SO_2 data base. Both data bases have representative and detailed meteorological data. The CCB data base provides a fine spatial resolution having some 94 tracer samplers; the TRC evaluation used 104 study hours. The Westvaco data base included a full year of hourly SO_2 data at 11 continuous-monitoring stations.

The eight complex terrain models evaluated on these data bases were described in Section 3, including COMPLEX I, COMPLEX II, COMPLEX/PFM, RTDM, PLUME5, 4141, SHORTZ, and IMPACT. The reader is referred to the TRC study report for an examination of the evaluation tests and the complete statistical results. The TRC report does not conclude which model performed best. It leaves the interpretation of the statistics largely to the readers.

As a separate activity within the EPA Meteorology and Assessment Division, a scientific review of the models tested is currently being performed. This separate, independent review will be based on an interpretation of the TRC statistical evaluation and also on a review of the theoretical bases of the model algorithms. Unfortunately, this separate review is not scheduled to be completed in time for input to this assessment document. The findings from the TRC evaluation that follow are therefore stated in relatively general terms and can be expected to be qualified or altered after the separate review is completed.

The TRC report presents eleven different statistical performance measures for each of the eight models tested. No recommendations are made regarding the relative importance of each of the performance measures. Both the Westvaco and CCB data bases are sorted into sets of the 25 highest values unpaired in time and space, the highest values for each event (paired in time), and all events paired in time and location. Statistics for 1-hour averaging times are presented for the CCB data base. Statistics for 1-, 3- and 24-hour averages are presented for the Westvaco data set. In addition, for the Westvaco data base, statistics for the highest and second-highest values are presented for each station. For both data bases, some breakdown of performance measures by meteorological condition and source receptor geometry is presented.

None of the models score "best" for all statistical measures and for all subsets of the data. Therefore the specific ranking of models based on the statistics depends upon one's weighting of the relative importance of the various measures. Nevertheless, some of the statistical measures are, in practice, somewhat redundant (such as differences of averages versus median difference; average absolute residual versus root-mean-square (r.m.s.) error; and the Pearson versus Spearman correlation coefficients). For overview purposes, it is possible to focus attention on a few of the performance measures.

Bias is an important measure because it characterizes a model's tendency to over- or underpredict. While minimum bias is statistically ideal, for EPA regulatory purposes overprediction is preferred to underprediction. The r.m.s. error is another important performance measure because it characterizes the variability of the observed versus predicted differences. The r.m.s. error squared can be shown to be approximately equal to the sum of the bias squared plus the standard deviation of the observed minus predicted residuals squared and as such, it includes consideration of the "noise" component of the residuals. Thus it would appear that, for EPA regulatory applications, the better models would show a minimum absolute value of bias, preferably where the bias is not significantly positive (tendency to under-predict), and minimum r.m.s. errors.

Tables 1 and 2 identify the models that showed superior performance by data subsets for the measures of minimum absolute value of bias, minimum r.m.s. error, minimum absolute value of bias if bias is less than or equal to zero, and minimum r.m.s. error if bias is less than or equal to zero. Table 1 addresses the Westvaco data set. For computational economy, the total 1-year data set was run for all models except IMPACT. A smaller subset of about 460 hours was used to test IMPACT with the other models. Table 2 presents the results for the CCB analyses in which all eight models were included in the comparisons.

Table 3 displays the relative rankings for the measures of minimum value of bias and minimum r.m.s. error. Considering first the total data set from Westvaco, the models that achieved the minimum absolute value of bias criteria for any of the given subsets were RTDM, 4141, and PLUME5. The model that had the lowest r.m.s. error for all categories was RTDM. The four models that did not show either lowest bias or lowest r.m.s. errors for any of the categories were COMPLEX I, COMPLEX II, COMPLEX/PFM, and SHORTZ. In the IMPACT case hours subset of the Westvaco data set, IMPACT also did not show either minimum bias or minimum r.m.s. errors. However, it did demonstrate minimum r.m.s. error for the CCB data base.

It is appropriate to try to identify some of the reasons for the differences in performance of the various models. First of all, for nearly all of the Westvaco data subsets, a comparison of the performance of COMPLEX I, COMPLEX II, and COMPLEX/PFM shows that COMPLEX/PFM outperformed the other two. COMPLEX II showed the greatest biases and r.m.s. errors. This suggests that the algorithms that are different in COMPLEX/PFM result in improvements. The primary differences are in the use of potential flow theory to develop plume trajectories when a nonzero H_c is calculated and the use of H_c in distinguishing the trajectories and the plume dispersion rates during stable conditions.

TABLE 1. MODEL PERFORMANCE FOR WESTVACO DATA BASE

Data Subset	Total data set					IMPACT case hours data subset				
	No. of data pairs	Lowest |bias|	Lowest r.m.s.	Lowest |bias| for bias≤0	Lowest r.m.s. for bias≤0	No. of data pairs	Lowest |bias|	Lowest r.m.s.	Lowest |bias| for bias≤0	Lowest r.m.s. for bias≤0
Highest 25 values unpaired in time, space										
1 hour	25	RTDM	NA*	RTDM	NA	25	RTDM	NA	RTDM	NA
3 hour	25	RTDM	NA	RTDM	NA	25	RTDM	NA	4141	NA
24 hour	25	RTDM	NA	4141	NA	25	NA	NA	NA	NA
Highest values paired by station										
1 hour	11	RTDM	RTDM	RTDM	RTDM	10	RTDM	RTDM	RTDM	RTDM
3 hour	11	RTDM	RTDM	RTDM	RTDM	10	RTDM	RTDM	PLUME5	4141
24 hour	11	RTDM	RTDM	4141	4141	10	4141	RTDM	SHORTZ	SHORTZ
Second highest values paired by station										
1 hour	11	RTDM	RTDM	RTDM	RTDM	10	RTDM	RTDM	PLUME5	4141
3 hour	11	RTDM	RTDM	4141	4141	10	4141	RTDM	4141	4141
24 hour	11	RTDM	RTDM	4141	4141	10	SHORTZ	RTDM	SHORTZ	SHORTZ
Highest values paired by event										
1 hour	~7200	4141	RTDM	4141	4141	~460	4141	RTDM	PLUME5	PLUME5
3 hour	~2400	4141	RTDM	4141	4141	~150	PLUME5	RTDM	PLUME5	PLUME5
24 hour	~360	4141	RTDM	4141	4141	~20	CX/PFM	RTDM	CX/PFM	SHORTZ
All values paired by time and space										
1 hour	~30000	PLUME5	RTDM	SHORTZ	SHORTZ	~2500	SHORTZ	RTDM	COMPLEX I	COMPLEX I
3 hour	~11000	PLUME5	RTDM	SHORTZ	SHORTZ	~860	SHORTZ	RTDM	COMPLEX I	COMPLEX I
24 hour	~3400	PLUME5	RTDM	SHORTZ	SHORTZ	~165	SHORTZ	RTDM	COMPLEX I	COMPLEX I

*NA - not applicable.

TABLE 2. MODEL PERFORMANCE FOR CINDER CONE BUTTE DATA BASE

	Total Data Set				
Data subset	No. of data pairs	Lowest |bias|	Lowest r.m.s.	Lowest |bias| for bias≤0	Lowest r.m.s. for bias≤0
Highest 25 values unpaired in time, space	25	RTDM	NA*	RTDM	NA
Highest values paired by event	104	RTDM	IMPACT	RTDM	RTDM
All values paired by time and space	3836	RTDM	IMPACT	RTDM	RTDM

*NA - Not applicable

TABLE 3. MODEL RANKINGS BASED ON TRC EVALUATION

Data subset	CXI		CXII		CX/PFM		RTDM		4141		PLUME5		SHORTZ		IMPACT**	
	*Bias	rms	Bias	rms	Bias	rms	Bias	rms	Bias	rms	Bias	rms	Bias	rms	Bias	rms
Westvaco Data Base																
Highest 25 values unpaired in time, space																
1 hour	6		7		5		1		2		4		3		7	
3 hour	6		7		4		1		2		5		3		7	
24 hour	6		7		4		1		2		5		3		NA[#]	
Highest values paired by station																
1 hour	5	4	7	7	6	6	1	1	2	2	4	5	3	3	8	8
3 hour	6	6	7	7	4	4	1	1	2	2	5	5	3	3	8	8
24 hour	6	5	7	7	4	4	1	1	2	2	5	6	3	3	8	8
Second highest values paired by station																
1 hour	5	6	7	7	6	5	1	1	2	2	4	4	3	3	8	8
3 hour	6	6	7	7	5	5	1	1	2	2	4	4	3	3	8	8
24 hour	6	6	7	7	4	4	1	1	2	2	5	5	3	3	8	8
Highest values paired by event																
1 hour	6	6	7	7	3	5	2	1	1	2	4	4	5	3	7	8
3 hour	6	6	7	7	3	4	2	1	1	2	4	5	5	3	7	8
24 hour	6	6	7	7	2	3	3	1	1	2	4	5	5	4	8	8
All values paired by time and space																
1 hour	6	6	7	7	2	5	4	1	3	2	1	3	5	4	8	8
3 hour	6	6	7	7	2	5	4	1	3	2	1	4	5	3	8	8
24 hour	6	6	7	7	2	3	4	1	3	2	1	5	5	4	8	8
Cinder Cone Butte Data Base																
Highest 25 values unpaired in time, space	3		8		5		1		7		6		4		2	
Highest values paired by event	3	3	8	8	5	4	1	2	7	5	6	6[+]	4	6[+]	2	1
All values paired by time and space	6[+]	3	6[+]	8	5	5	1	2	8	7	4	6	2	4	3	1

*Minimum absolute value of bias. [#] NA - Not applicable. [+] Identical rankings.

**IMPACT ranking for Westvaco calculated on IMPACT case hours data subset.

Along the same lines, the features of COMPLEX I, COMPLEX II, and COMPLEX/PFM that probably account for the major differences in their bias versus the bias of other models are the level plume/10-m minimum approach algorithm in combination with the dispersion coefficients for strongly stable conditions. These features apparently cause these models to overpredict. Model 4141, which uses the same diffusion coefficients, utilizes a 0.25 terrain correction factor under the same conditions and has less bias and smaller variances. The SHORTZ model uses similar trajectory assumptions as COMPLEX I and II for stable conditions if the plume lies within the mixed layer, but uses on-site turbulence data for the computation of dispersion coefficients. The fact that SHORTZ performs better than COMPLEX I and II suggests that the dispersion rates are better parameterized in this model. RTDM also uses on-site turbulence statistics and assumes either a 0.5 terrain correction factor for the plume height relative to H_c if the plume is above H_c or direct impact if the plume is below H_c. RTDM appears to perform better than SHORTZ in predicting the highest values, reinforcing the notion that the trajectory assumptions in COMPLEX I and II need improvement. The ranking of performance of the other models did not change appreciably with changes in averaging time.

For the CCB data set, the RTDM, SHORTZ, COMPLEX II, and COMPLEX/PFM models showed performance consistent with that achieved with the full Westvaco data set. IMPACT, which ranked relatively poorly for the Westvaco tests, ranked highly at CCB. COMPLEX I also showed improved performance at CCB where the average of the highest 25 predicted values was within a factor of 2 of the observed. Model 4141, on the other hand, showed considerably poorer performance at CCB. One difference in the two complex terrain settings is the roughness of the upwind fetches. Relatively flat terrain surrounds CCB, whereas Luke, Maryland is surrounded by mountainous terrain. The fact that the RTDM and SHORTZ models use on-site turbulence data may be one reason that their performance is consistent at the two sites.

It should be noted that differences in the model rankings in Table 3 were occasionally minimal or even nonexistent as in two of the CCB data subsets. Consideration of additional statistics in the TRC report is suggested to present a complete record of model performance.

ERT EVALUATION OF COMPLEX TERRAIN DISPERSION MODELS

The most recent complete evaluation of the Complex Terrain Dispersion Model (CTDM) using Cinder Cone Butte (CCB) data is reported in the Third Milestone Report (Lavery et al., 1983b). This evaluation intercompares Valley, COMPLEX I, COMPLEX II, and CTDM version 11083. Note, however, that the CTDM version described in Section 3 is a more recent upgrade that has not been fully evaluated at this time, although the terrain-enhanced σ_z form (11083-E) is similar in many respects. Model comparisons are based on the results from 153 tracer hours of data from the CCB experiments.

Overall residual statistics developed by comparing model calculations with tracer gas concentrations sampled at CCB are given in Table 4. The columns labeled "Peak concentrations" in Table 4 summarize the error in estimating 1-hour maximum concentrations, regardless of location, over the 153 tracer hours. The columns titled "All concentrations" summarize the mean errors in estimating concentrations observed at all sampling points (paired in space and time).

TABLE 4. SUMMARY* OF RESIDUAL STATISTICS FOR MODEL COMPARISON

Model	Peak concentrations (unpaired in space)						All concentrations		
	m_a	s_a	r_a	m_g	s_g	r_g	m_a	s_a	r_a
CTDM(11083-E)	3.3	27.4	0.90	1.37 (1.23)	3.2 (3.3)	0.99	0.50	12.7	1.13
CTDM(11083)	2.8	33.7	0.88	2.08 (1.70)	6.9 (5.2)	1.18	-0.51	15.4	1.01
Valley	-41.0	25.5	1.63	0.24	3.0	5.52	--	--	--
COMPLEX I	-15.0	37.9	0.93	0.65 (0.53)	3.8 (3.2)	1.29	-6.04	21.9	0.99
COMPLEX II	-60.1	99.7	0.94	0.38 (0.32)	5.0 (4.6)	1.09	-5.61	36.9	0.99

Note: ( ) values of m_g, s_g are calculated directly from the C_o/C_p ratios, with the $C_p = 0$ values removed.

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*Based on the 153 tracer hours from the Cinder Cone Butte data base. Arithmetic m_a and s_a statistics carry units of $10^{-6} s/m^3$ or $\mu s/m^3$.

The residual statistics suggest that CTDM(11083-E) has the best overall performance. The CTDM(11083-E) log-normal statistics for bias (m_g) and noise (s_g) are close to the desired value of 1.0, and the corresponding arithmetic statistics (m_a and s_a) of the set of paired concentrations are the lowest of all the models. CTDM(11083-E) and CTDM(11083) underestimate peak concentrations while COMPLEX I overestimates them.

COMPLEX II and Valley simulate the observations much more poorly than do the other models. Both models substantially overestimate the peak concentrations, and COMPLEX II does a poor job in reproducing the distribution of the tracer gas concentrations observed on CCB. The measure of model resolution (r) identifies Valley as less responsive to changes in meteorology for predicting peak concentrations than the other models, but the resolution statistics of the other four models are not significantly different. Figure 5 shows plots corresponding to Table 4 of the log-normal and arithmetic performance statistics based on residuals of the peak observed and peak modeled concentrations for the five models.

Scatter plots of peak observed concentrations scaled by the emission rate (C_o/Q) versus peak modeled concentrations scaled by the emission rate (C_p/Q) show that three of the models exhibit qualitatively similar patterns, while two show patterns that are distinctly different from the rest (Figure 6).

The Valley model is not designed to use on-site meteorological measurements, but uses "worst-case" meteorology instead. Therefore, model estimates of C_p/Q depend only on the distance from the source of the nearest terrain feature at the elevation of the release. At CCB, this leads to a relatively narrow band of C_p/Q values that is unlike the pattern of the other models evaluated. Valley overestimates most C_o/Q values, but it underestimates the seven largest C_o/Q values. This indicates that the standard "worst-case" meteorological conditions contained in Valley for screening large power plant plumes are probably not appropriate on the scale of the CCB tracer plumes.

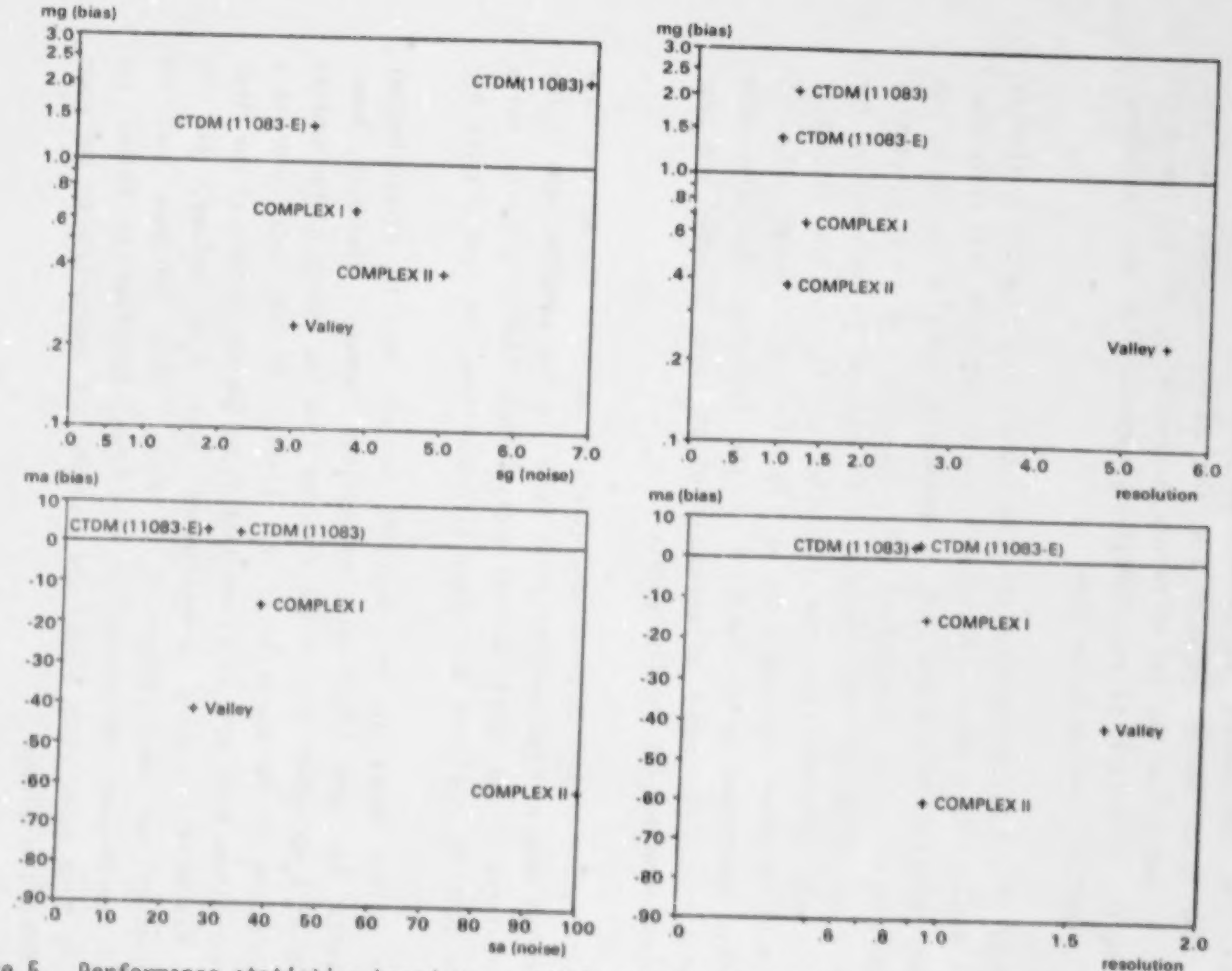

Figure 5. Performance statistics based on residuals of peak observed and peak modeled concentrations for five models as applied to 153 hours of Cinder Cone Butte tracer data.

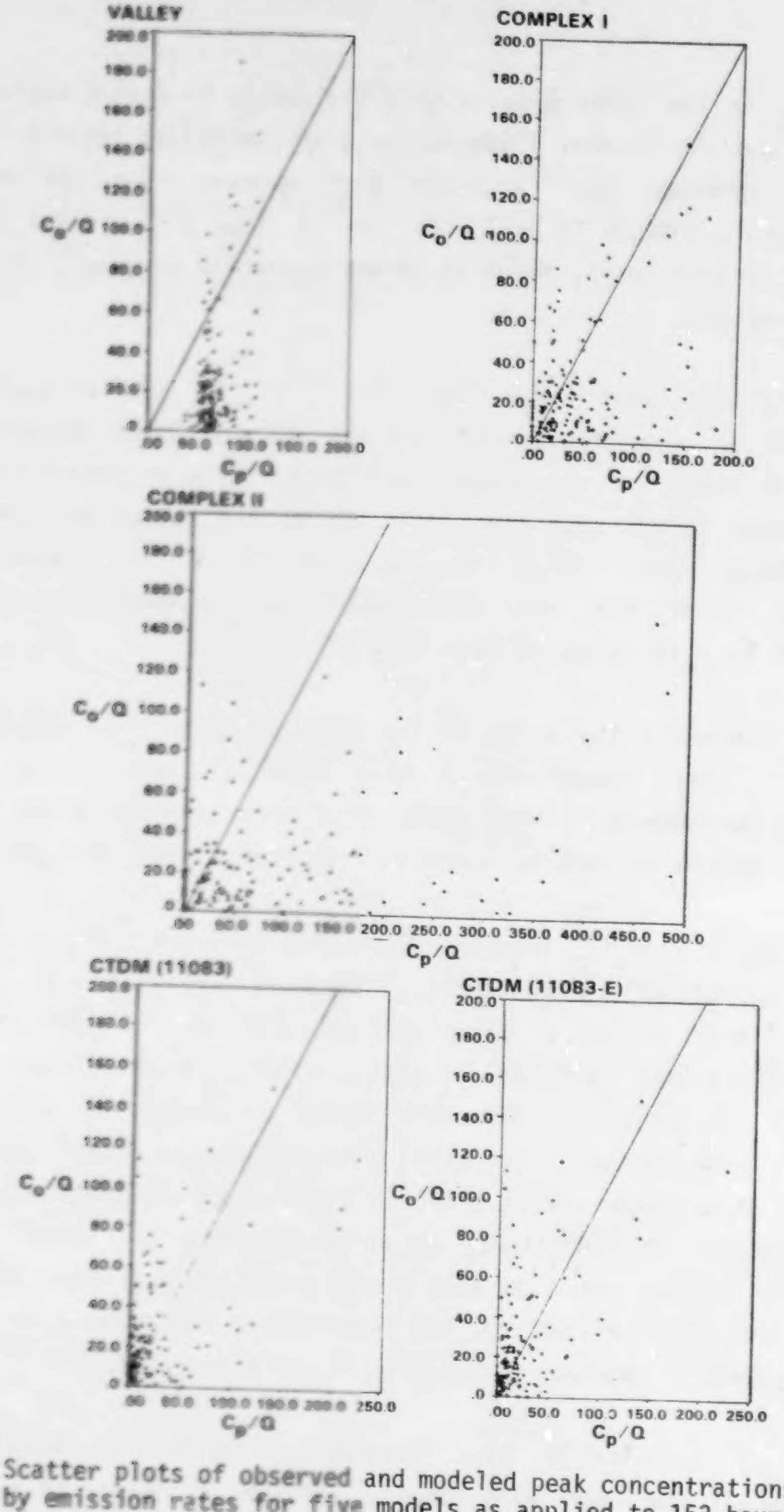

Figure 6. Scatter plots of observed and modeled peak concentrations normalized by emission rates for five models as applied to 153 hours of Cinder Cone Butte tracer data.

COMPLEX II is the other model with a distinctly different scatter plot pattern. This pattern is nearly the opposite of the Valley pattern. Valley concentration estimates cover a range much narrower than the range of observations, while COMPLEX II estimates cover a range much greater than the observations. In both cases, model estimates appear to be poorly correlated with the observations.

COMPLEX I, CTDM(11083), and CTDM(11083-E) display similar patterns of scatter in that the range of estimated and observed peak hourly concentrations are nearly the same, and the visual correlation between observations and estimates is much better than that indicated by the Valley and COMPLEX II patterns. Among these three models, COMPLEX I is biased toward overestimation; CTDM(11083) and CTDM(11083-E) are somewhat biased toward underestimation of C_o/Q values of less than 100.

To help understand the noise in the model calculations, the residuals based on the peak concentrations have been plotted against several meteorological parameters. These plots show where a model might be doing comparatively better or worse, thereby indicating areas for improvement.

Scatter plots of C_o/C_p (between 0 and 10) vs. wind speed are given in Figure 7 for CTDM(11083), CTDM(11083-E), COMPLEX I, and COMPLEX II. There is considerable scatter in all of the plots, but some trend can be seen in the patterns. CTDM(11083) exhibits a distinct bias toward underestimating observed peak concentrations for wind speeds in excess of about 5 m/s. Because H_c is probably small (or zero) compared to the source heights when source-height wind speeds are as great as 5 m/s, this tendency suggests that the LIFT component of CTDM(11083) is underestimating the amount of plume material on the surface under the more nearly "neutral" flow conditions. When σ_z is enhanced as in CTDM(11083-E), the figure shows that much of this bias at larger wind speeds is reduced, although it is not eliminated.

COMPLEX I exhibits a bias towards overestimating peak observed concentrations at the lower wind speeds. COMPLEX II appears to exhibit the same behavior, except that a few large underestimates also occur at light wind speeds. The overestimates for light winds may be the result of using

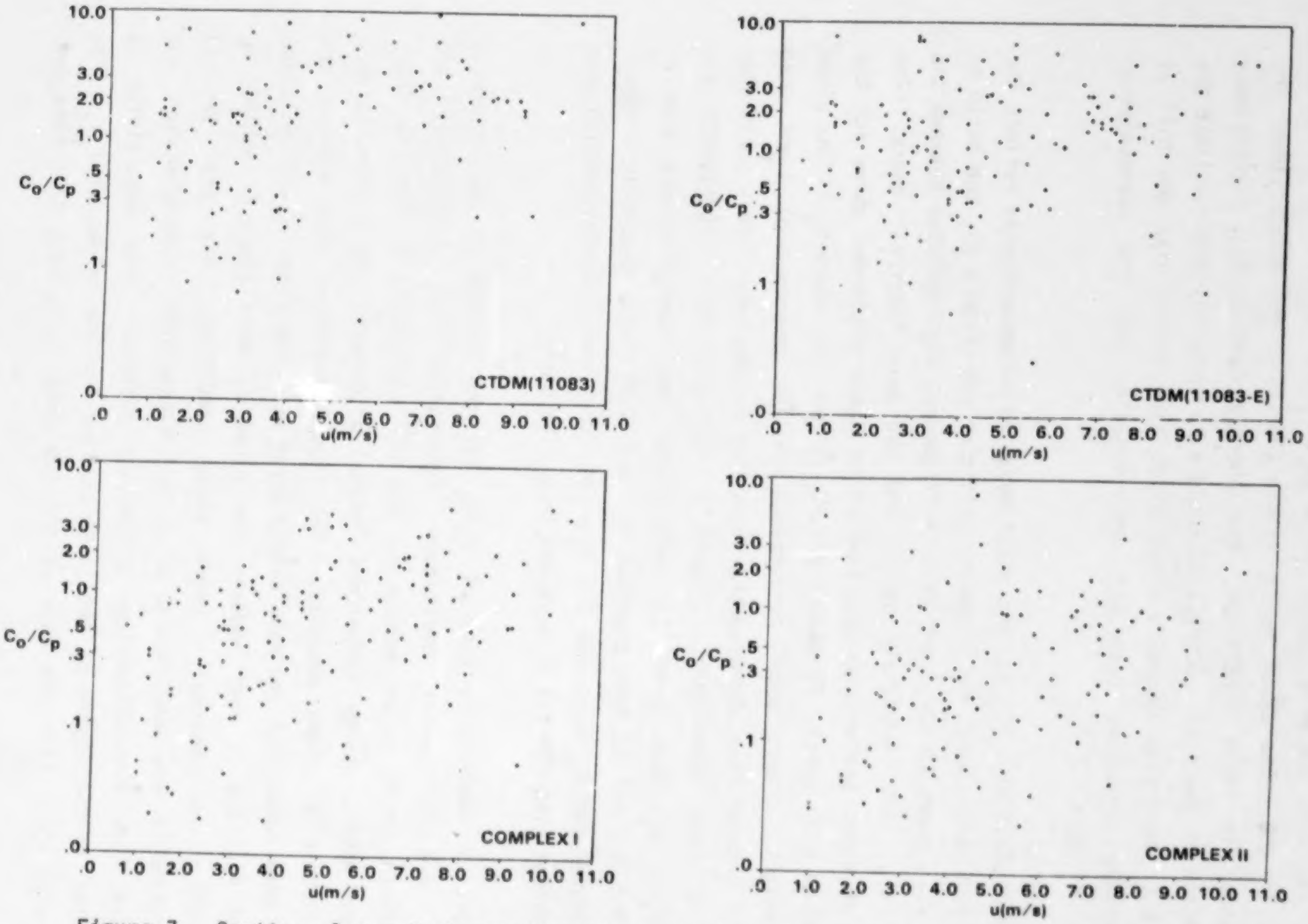

Figure 7. Scatter plots of observed/modeled concentration ratios versus wind speed for four models as applied to 153 hours of Cinder Cone Butte tracer data.

Pasquill-Gifford-Turner σ_y values in COMPLEX II and 22.5° sector-averaging in COMPLEX I. At very low wind speeds, the wind direction often underwent large variations at CCB. The 22.5° sector within COMPLEX I may underestimate the plume meander in these conditions, and thereby consistently overestimate concentrations on the hill. COMPLEX II would also certainly underestimate the meander, but its narrow Gaussian plume might also nearly miss the hill at times, thereby producing both the underestimates and the overestimates indicated in Figure 7.

Scatter plots of C_o/C_p against other modeling parameters also reflect the patterns just described. For example, parameter u/N (Figure 8), the ratio of the mean wind speed to the Brunt-Vaisala frequency, distinguishes between the "stable" (e.g., u/N relatively small) and the more "neutral" hours. The patterns of model performance are similar to those discussed above for the plots against wind speed. Parameter $1-H_c/H_s$ (Figure 9), where H_s is the plume release height, orders model performance in the near-neutral limit when $1-H_c/H_s$ is greater than approximately 0.5, and in the very stable limit when $1-H_c/H_s$ is less than zero. Figure 9 indicates that CTDM(11083) and CTDM(11083-E) are most prone to overestimate peak concentrations when H_c exceeds 0.5 H_s, but is less than 1.5 H_s, and CTDM(11083) generally produces underestimates for H_c less than 0.5 H_s. The bias toward overestimating peak concentrations with COMPLEX I increases as H_c increases.

Figure 10 contains a plot of C_o/C_p vs. the product of the crosswind vertical and horizontal turbulence intensities for CTDM(11083) and CTDM(11083-E). (The other models in the ERT evaluation do not use these turbulence data.) Large turbulence intensity products imply a relatively large dilution of plume material. The figure indicates that modeled and observed peak concentrations most nearly agree when the plume is well diluted. When the dilution is much weaker, the plume is more compact, exhibiting considerably less meander. Under these conditions, the peak modeled concentration is very sensitive to plume path assumptions, wind direction, and postulated flow distortion/plume dispersion effects. This sensitivity is illustrated in the figure by the large scatter for low values of $i_y i_z$. The figure also shows that the bulk of the CCB data falls into this category.

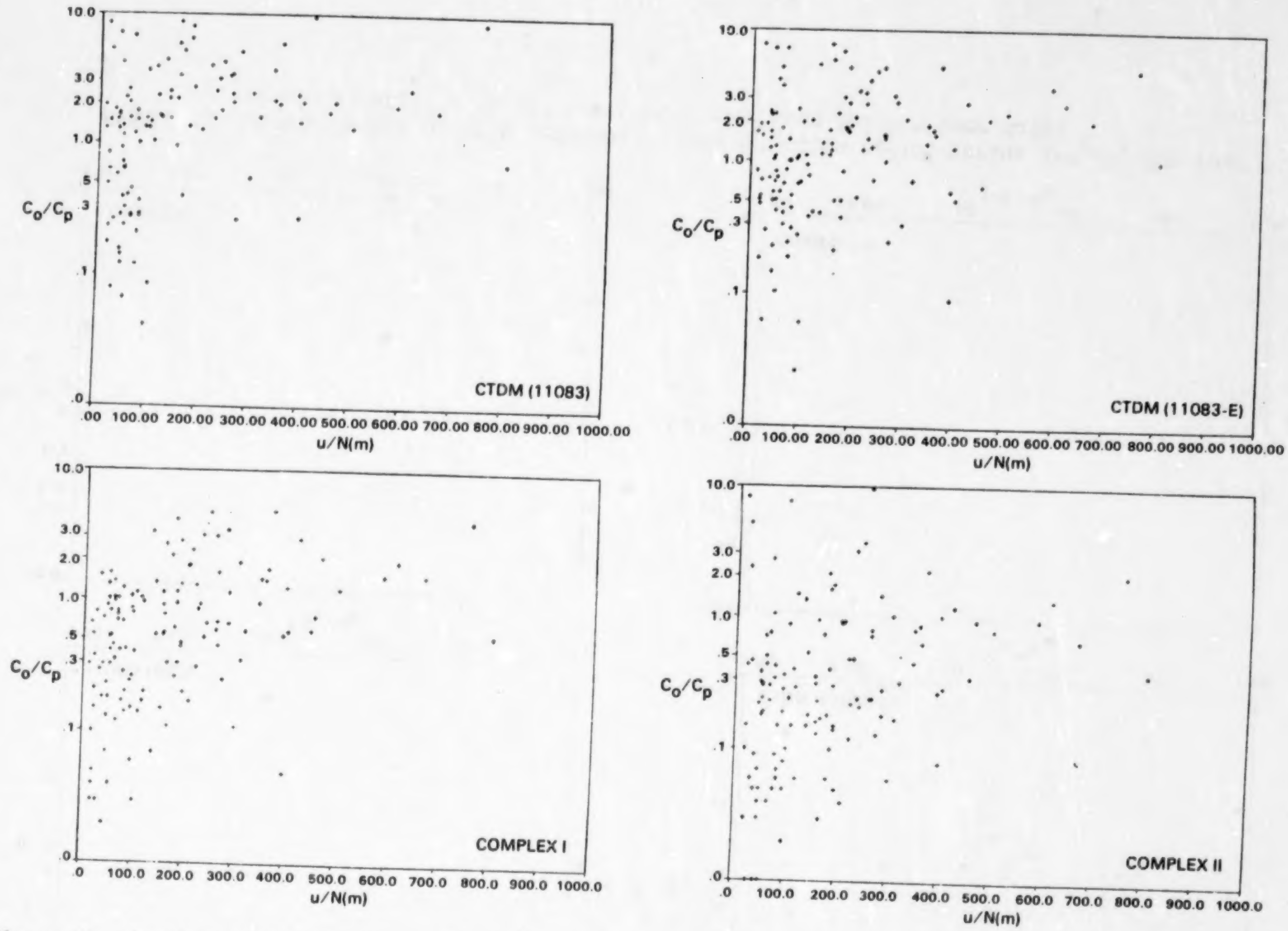

Figure 8. Scatter plots of observed/modeled concentration ratios versus ratio of wind speed/Brunt-Vaisala frequency for four models as applied to 153 hours of Cinder Cone Butte tracer data.

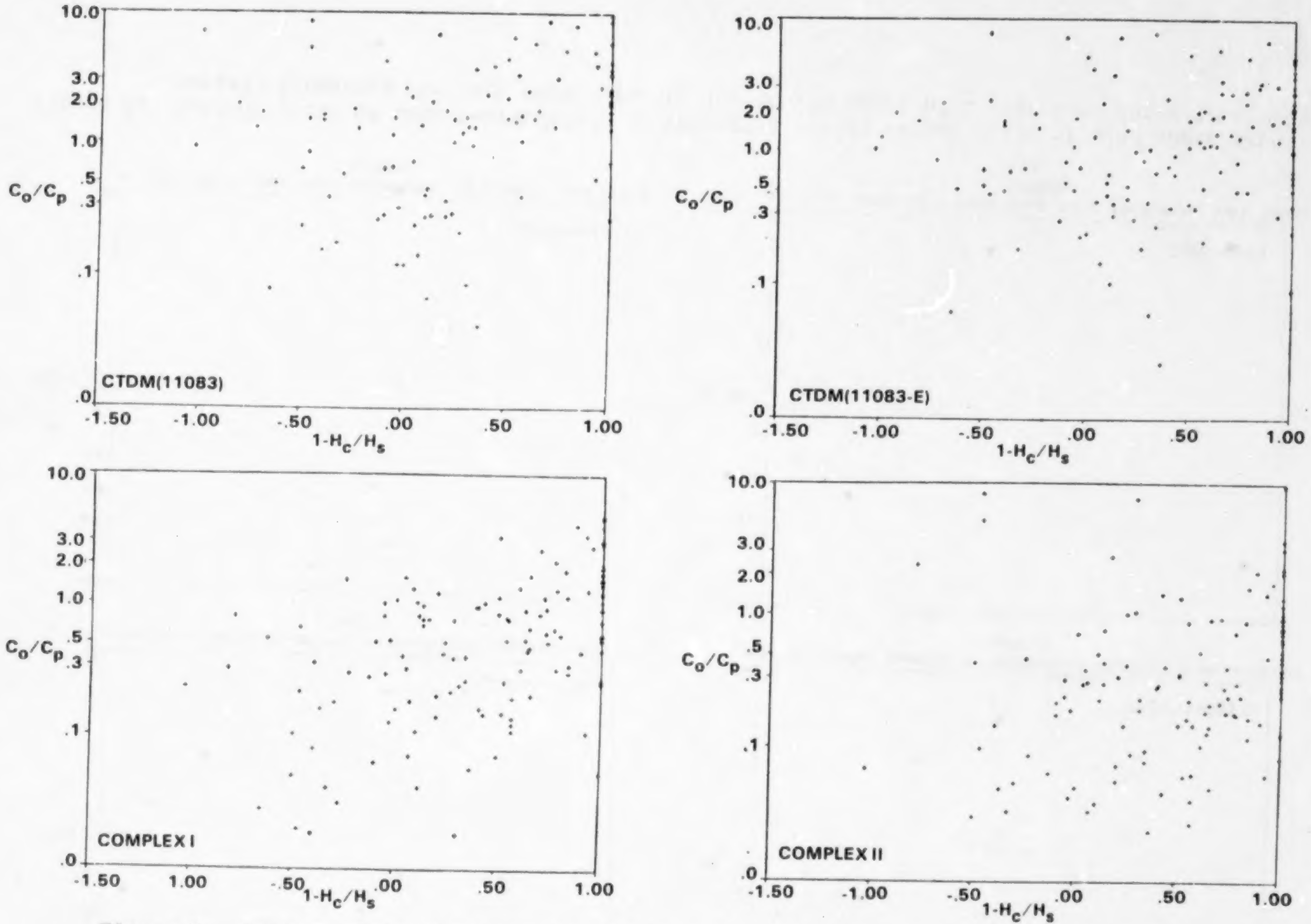

Figure 9. Scatter plots of observed/modeled concentration ratios versus $1-H_c/H_s$ for four models as applied to 153 hours of Cinder Cone Butte tracer data.

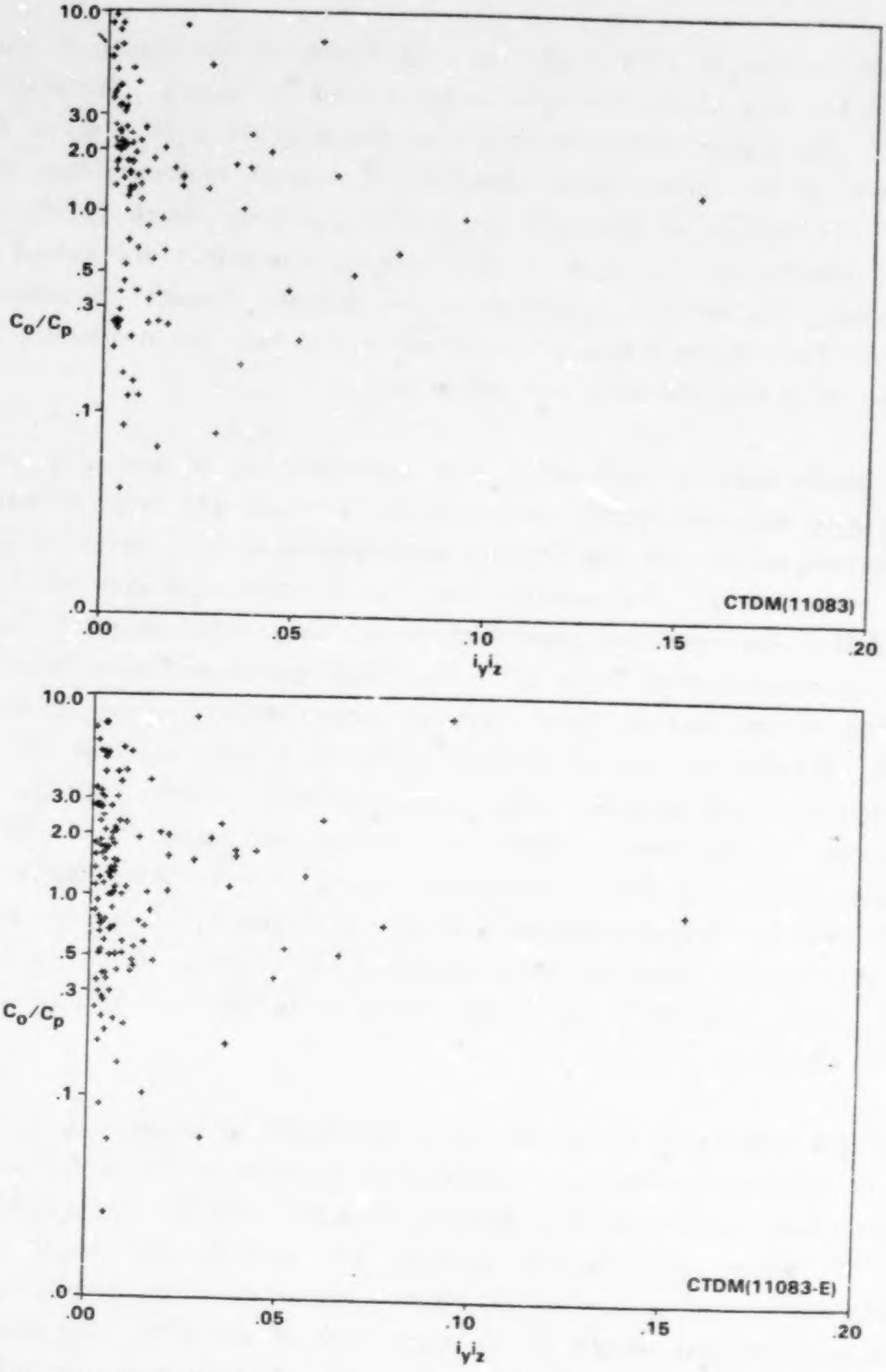

Figure 10. Scatter plots of observed/modeled concentration ratios versus product of turbulence intensities for two models as applied to 153 hours of Cinder Cone Butte tracer data.

A recent version of CTDM(03184) has been tested on the "neutral" hours from the CCB SF_6 data base. The results are listed in Table 5. The measure of how well the higher concentrations are simulated is C_o/C_p, where the geometric mean of the three highest observed and modeled concentrations form the ratio. The measure of how well the overall patterns match is r^2, the correlation coefficient for observed and modeled concentrations paired in space and time. The relative magnitude of the observed "impact" is measured by C_oU/Q. In Table 5, this scaled concentration has been divided by 100 for convenience. Note that the units are ppT-m/100g.

Model performance in estimating peak concentration is generally worse when the scaled observed "peak" concentration is relatively large or small. The two greatest values (360 and 379) are associated with C_o/C_p values of 8.76 and 4.90, respectively. The lowest value (73) is associated with the C_o/C_p value of 0.37. The remaining experiment hours have scaled observed "peak" concentrations ranging from 104 to 303. The "peak" impact estimated from CTDM is presented as the scaled "peak" modeled concentration in the table for comparison. Results for the two experiment 202 hours stand out from the rest in that the scaled peak observed values are considerably greater than the rest of the hours in the table, while the scaled peak modeled values are considerably smaller. A direct impingement of the plume on the windward face would be needed to even approach the size of the observed peak concentrations in each case. Because these two hours appear to be outliers and are so unlike the others, they have been set aside during performance of the following statistical analyses.

Model performance in estimating the distribution of plume material over the hill is characterized by the r^2 statistic. Relative to the performance in most hours, experiments 201(18), 202(19), 214(10), 218(3), and 218(6) are subpar. Of these, 202(19) and 214(10) are clearly the worst. The concentration distribution for 202(19) shows a region of higher concentrations below the plume release height on the north side of the hill. The model is incapable of bringing plume material to the surface in this area. In 214(10), it appears as though the plume experienced a more northerly component than indicated by the data archive (the release was northwest of the hill). Nonetheless, the magnitudes of the concentration estimates are similar to the magnitudes of the observations for this hour.

TABLE 5. CTDM(03184) MODELING RESULTS FOR NEUTRAL HOURS OF CINDER CONE BUTTE DATA BASE

Experiment (hour)	H_s	$U(H_s)$	$H_s'^{*}$	$C_o^{\#}$	$C_p^{\#}$	$Q(g/s)^{+}$	r^2	C_o/C_p	$\frac{C_oU}{100Q}$	$\frac{C_pU}{100Q}$
201(18)	30	6.8	27.2	401	222	.090	0.16	1.81	303	167
202(18)	50	10.3	48.1	206	42	.056	0.43	4.90	379	77
202(19)	50	9.9	48.1	298	34	.082	0.02	8.76	360	41
214(10)	24	2.4	19.3	834	1668	.124	0.01	0.50	161	322
217(9)	40	6.7	37.1	330	224	.139	0.92	1.47	159	108
217(10)	40	5.8	35.8	360	363	.139	0.82	0.99	150	152
218(3)	30	5.5	26.3	174	470	.131	0.36	0.37	73	197
218(4)	30	6.7	26.8	561	240	.151	0.72	2.34	249	106
218(5)	30	8.7	27.1	439	323	.156	0.78	1.36	245	180
218(6)	30	8.1	27.0	185	215	.144	0.31	0.86	104	121
218(7)	30	7.2	27.3	315	217	.133	0.54	1.45	171	118
218(8)	30	7.9	27.4	411	351	.155	0.74	1.17	209	179
218(9)	15	6.9	12.0	404	500	.130	0.68	0.81	214	264
218(10)	15	8.5	12.3	345	473	.146	0.50	0.73	201	275

* H_s' is the effective plume elevation after accounting for shear and buoyancy.

# Geometric mean of the three largest concentrations (ppt).

+ Effective hourly emission rate.

The overall model performance for the 12 hours remaining after removing experiments 202(18) and 202(19) can be characterized by the r.m.s. error and bias of the observed and modeled concentrations. For all concentrations paired in space and time, r.m.s. error = 1459 ppT-s/g and bias = 37 ppT-s/g, where the mean value of the observations is 782 ppT-s/g. For the highest and second highest observed and predicted concentrations paired by event, the r.m.s. error and bias equal 5233 and -1180 ppT-s/g, respectively, for the highest, and equal 1941 and -230 ppT-s/g for the second highest. The mean observed concentrations are 3231 and 2971 ppT-s/g, respectively. If the r.m.s. error is squared and scaled by $\bar{C}_0^2$ to characterize the performance for these 12 hours, we obtain the r.m.s./$\bar{C}_0^2$ value of 3.48 for all concentrations paired by event, and values of 2.62 and 0.43 for the highest and second highest concentrations paired by events.

The pattern of observed and modeled concentrations in 214(10) prompted two modifications. The first was to re-evaluate the winds used to drive the model, and the second was to try modeling each 5-min period individually when the meteorology appeared to vary significantly during the hour. Wind directions for 214(10) were estimated to be consistent with the impact zones resolved by the 10-min samplers; 10-m wind directions measured by the cup-and-vane sets were substituted for 218(3) and photo estimates of wind direction were substituted for 201(18). Furthermore, the 5-min simulation was selected for 201(18), 214(10), 218(4), 218(5), 218(6), 218(7), and 218(10). Hours 217(9), 217(10), and 218(9) were judged to be insensitive to alternate wind direction estimates and the 5-min simulation technique.

These model runs are generally more successful than the previous runs. Experiment 214(10) in particular shows a dramatic improvement. This improvement is, no doubt, due in part to "fixing" the modeling wind directions to conform with the tracer results, but an equally important element is the use of the sequence of 5-min meteorology. As a morning transition hour, the temperature structure and the turbulence changed significantly during the hour. An explicit modeling of such changes appears necessary to providing good modeling results.

Overall statistics for the second modeling runs can be formed by including the results for those hours not remodeled, and excluding 202(18) and 202(19). The r.m.s. error and bias for all concentration residuals equal 917 and 0.5 ppT-s/g, respectively, with a mean observed concentration equal to 782 ppT-s/g. These values represent a substantial improvement. For the highest and second highest observed and predicted concentrations paired by event, the r.m.s. error and bias equal 1562 and 114 ppT-s/g for the highest, and 1204 and 68 ppT-s/g for the second highest.

Again, these statistics indicate a substantial improvement in model performance. The r.m.s. error for the three sets of data pairs drops by approximately 40% or more, and the bias values lie much closer to zero. In terms of the performance measure, r.m.s./$\bar{C}_o^2$, these data produce 1.38 for all concentrations paired by event, and 0.23 and 0.16 for the highest and second highest concentrations paired by event.

These results show that the newer version of CTDM does very well in estimating the peak observed concentrations for the neutral hours ($H_c = 0$) in the CCB data base, especially when the "unexplainable" hours are removed. The tendency toward underestimating the peak concentrations seen in CTDM(11083) is virtually absent. Because H_c is zero in these experiment hours, the success of CTDM(03184) is attributed to its σ_y and σ_z formulations (with detailed on-site turbulence measurements), and its method for incorporating terrain effects in the limit of weak stratification.

SECTION 5

FLUID MODELING STUDIES OF COMPLEX TERRAIN DISPERSION

INTRODUCTION

Wind tunnel studies of the dispersion of pollutants from industrial plants located in or near mountainous terrain have been conducted over the last four decades. These studies were generally performed to answer specific engineering questions such as good-engineering-practice stack heights or locations to avoid aerodynamic downwash. The results have not been generally transferable to other sites. More recently, studies have attempted to simulate the atmospheric boundary layer including stratification, and to investigate the effects of wind shear and turbulence intensity. These generic studies have utilized idealized terrain features to understand the basic physical processes of complex terrain transport and diffusion.

Laboratory experiments are probably most useful as a complement to other forms of complex terrain research -- theoretical modeling and field observations -- but in some circumstances they may provide the only practical and economically viable means of studying a problem. A main advantage of laboratory experiments is the opportunity to isolate a particular meteorological phenomenon from the complexity of others occurring simultaneously and then to study that phenomenon over a range of controlled conditions.

The general requirements for attaining similarity between laboratory and full-scale flows are addressed in several articles (e.g., Cermak et al., 1966; Snyder, 1972; Cermak, 1976; Snyder, 1981) and are generally agreed upon. Besides matching the boundary conditions, strict similarity requires the equality of four dimensionless parameters in model and prototype: the Rossby number, the Reynolds (Re) number, the Froude (Fr) or bulk Richardson (Ri_b) number, and the Peclet (Pe) number. For the typical (although not exclusive) problem in which Coriolis effects are not simulated, the Rossby number is not matched. In addition, the Reynolds and Peclet numbers need not be matched, provided that Re exceeds some critical value, i.e., large scale turbulence is independent of Re. The single most important parameter that must be simulated is Fr, which measures the ratio of inertial to buoyancy forces in the flow. The importance of simulating buoyancy forces cannot be overemphasized for atmospheric problems. This buoyancy simulation is basically what sets laboratory simulation of atmospheric flows apart from that of neutrally stratified shear flows which are more typical in mechanical and aerospace engineering applications.

The Rossby number represents the ratio of advective or local accelerations to Coriolis accelerations. Snyder (1981) concluded from a review of the literature that the Rossby number needs to be considered when modeling prototype flows with length scales greater than about 5 km under neutral or stable conditions in relatively flat terrain. In modeling flows in complex terrain, we may expect local accelerations to be much more significant than in flat terrain; therefore, prototypes with length scales significantly larger than 5 km may be modeled ignoring the Rossby number. Despite this apparent relaxation of Rossby number similarity in complex terrain, very few fluid modeling studies have considered length scales larger than a few km.

This section attempts to summarize the results of recent stratified towing-tank and wind tunnel studies designed to obtain basic understanding of flow and diffusion in complex terrain. The summary follows the recent reviews by Snyder (1984a, 1984b) and highlights the work at the EPA Fluid Modeling Facility at Research Triangle Park, North Carolina.

STABLE FLOW SIMULATIONS

Although the complete physics of dispersion around obstacles in stably stratified flows is complicated and only partially understood, for an ideal flow with a constant velocity U_0 and Brunt-Vaisala frequency N approaching a hill of height h, the essential flow properties are described by the hill Froude number, Fr

$$Fr \equiv U_0/Nh. \tag{39}$$

The hill Froude number is the square root of the ratio of the kinetic energy of the approaching fluid to the potential energy it acquires in surmounting the hill.

Experiments and theory (Sheppard, 1956; Drazin, 1961; Hunt and Snyder, 1980; Snyder et al., 1980; Rowe et al., 1982) indicate that the Froude number divides the atmosphere (or fluid) into two distinct regimes of flow about the hill (Figure 11). In region 1, which extends from the base of the hill to a height h(1 - Fr), the flow does not have enough kinetic energy to go over the hill and remains roughly horizontal as it goes around the hill. (On the downwind side, this flow separates into a horizontally recirculating wake.) In region 2, which lies above the dividing streamline that separates the two regions, the flow has enough energy to pass up and over the hill. The concept of the dividing-streamline height $H_c \equiv h(1 - Fr)$ is related to the notion that a fluid parcel can rise only through a height U_o/N.

If the wind speed and stratification are functions of height (as is generally the case), H_c is defined as follows

$$\frac{1}{2} U^2(H_c) = \int_{H_c}^{h} N^2(z)(h - z)dz \tag{40}$$

where U is the wind speed at $z = H_c$ and N(z) is the local Brunt-Vaisala frequency defined by

$$N(z) = [g/\theta(z)\ (\partial\theta/\partial z)]^{\frac{1}{2}} \tag{41}$$

where g is the acceleration due to gravity and θ is the potential temperature (°K). The left-hand side of Equation 40 is the kinetic energy of the fluid at $z = H_c$, and the right-hand side is the potential energy gained by the fluid in rising through the height $h - H_c$.

Note that H_c, as defined, depends only on the height of the hill; it does not account for the shape of the hill as "seen" by the flow. We do not expect a sharp boundary between regions 1 and 2; nevertheless, the concept of a well-defined H_c is useful in studying stable flows over hills.

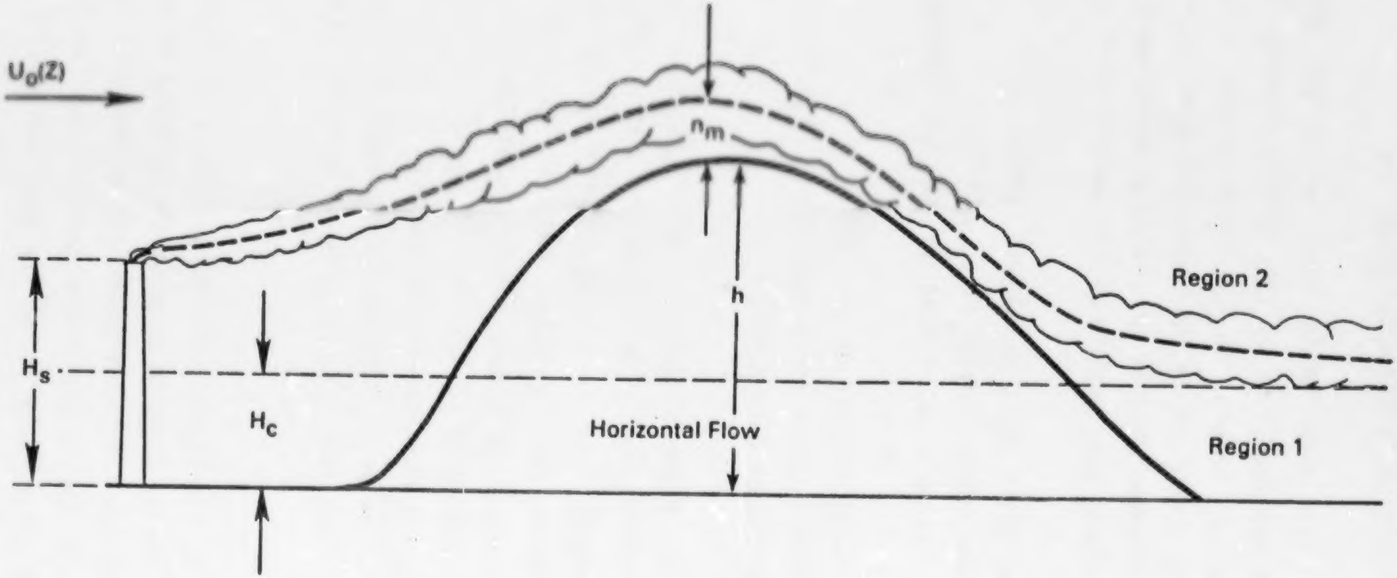
$U_o(Z)$
η_m
h
Region 2
H_s
H_c
Horizontal Flow
Region 1

Figure 11. Schematic diagram of plume behavior in stable flow around a terrain obstacle.

Verification of the Dividing-Streamline Concept

Several towing tank experiments were run at the EPA Fluid Modeling Facility to test the applicability of the integral formula (Equation 40) for the dividing-streamline height in strongly stable flows over hills. Additional tests were conducted in the stratified wind tunnel of the National Institute for Environmental Studies of the Japan Environment Agency (Ogawa et al., 1981). Simulations were performed for several hill shapes and aspect ratios, e.g.,

- bell-shaped hills (Hunt and Snyder, 1980),
- cone and hemisphere (Snyder et al., 1980),
- truncated, steep-sided ridges of various crosswind aspect ratios (Castro et al., 1983),
- vertical fences (Snyder et al., 1982),
- "infinite" triangular ridge and a long sinusoidal ridge, and
- a model of Cinder Cone Butte.

The concept of H_c was found to be valid when interpreted as a necessary but not sufficient condition for wide ranges of hill shapes, density profile shapes and wind angles, and in strong shear flows as well. For example, Figure 12 illustrates the composite estimates of the plume paths and dispersion for a towing tank simulation of Cinder Cone Butte. Dye streamers were released at 0.125, 0.25, 0.375, 0.5, 0.75, and 1.25 of the hill height. The qualitative results corroborate the suggestions of Hunt and Snyder (1980) that plumes released below H_c tend to impinge upon and pass around the sides of the target hill and that plumes released above H_c tend to pass over the hillcrest.

Twelve tows of the Cinder Cone Butte model were performed in the Fluid Modeling Facility towing tank to examine the validity of the integral formula (Equation 40) for the dividing-steamline height with non-uniform density gradients. For each tow, a particular source height was chosen and Equation 40 was integrated numerically using the measured density profile to predict the towing speed required such that the center tracer streamer (of three) would rise just to the elevation of the saddle point, i.e., the minimum height of the draw between the two peaks of Cinder Cone Butte. If the formula were

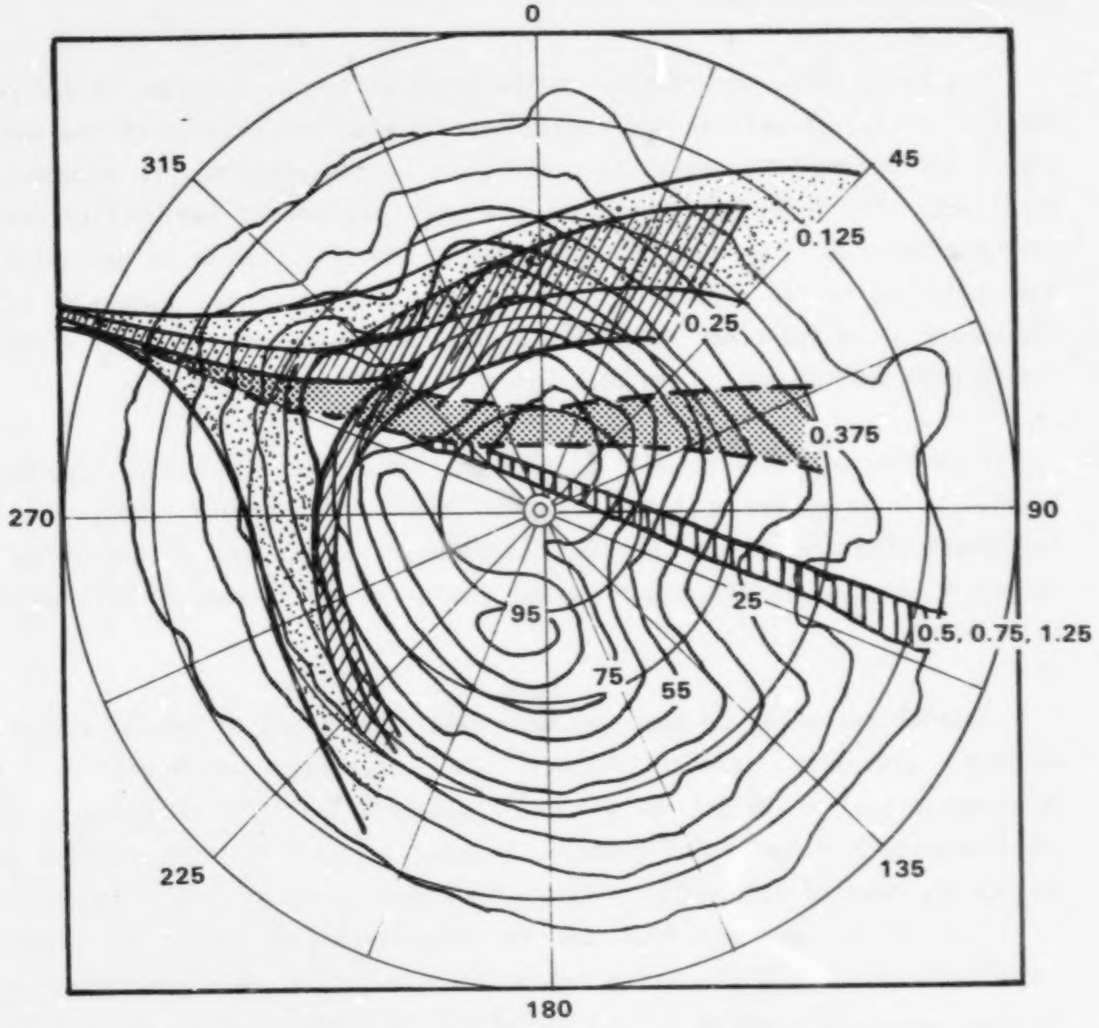

Figure 12. Composite estimates of plume paths based on towing tank simulations of Cinder Cone Butte model.

correct, the lower streamer would be observed to go around the sides of the hill, the upper streamer over the top, and the center one, because of its finite thickness, would split with the upper portions going over and the lower portions around the sides.

Figure 13 shows the results of the integrations of Equation 40 for each density profile as well as the experimentally observed results of the twelve tows. The agreement between the predictions and observations is regarded as excellent. The error bars indicate the best judgment of variability during the observations. For example, tow number 0 showed little or no deviation of the splitting of the center streamer, so that the error was judged as zero. Tow number 3, on the other hand, showed occasional wisps of the lower streamer rising over the top and of the upper streamer going around the hill.

From previous work as well as current studies with the Cinder Cone Butte model, it is concluded that the integral formula of Sheppard (1956) is valid for predicting the height of the dividing streamline for a wide range of shapes of stable density profiles and a wide range of roughly axisymmetric hill shapes.

Another series of 12 tows was made with steep-sided triangular ridges of various crosswind aspect ratios to ascertain effects on the dividing-streamline height as a three-dimensional hill is elongated into a two-dimensional ridge. For example, Figure 14 shows the observations made during the tows of triangular ridges with aspect ratios of 1 ($L = h$) and 8 ($L = 8\ h$). It is apparent that the dividing-streamline height followed the "1-Fr" rule for $Fr \leq 0.25$, and deviated strongly for $Fr > 0.25$, but there were no observable differences due to variations in aspect ratio. The deviation from the "1-Fr" rule is due to the formation of an upwind vortex that produces a downward flow on the front face of the ridge. It is apparently due to the combination of the steep upwind slope of the ridge and the shear in the approach flow.

Notice that the data in Figure 14 are on the opposite side of the "1-Fr" line from the "1-2Fr" line suggested by Baines (1979), even for the ridge with aspect ratio 8. From the studies with the truncated triangular and sinusoidal

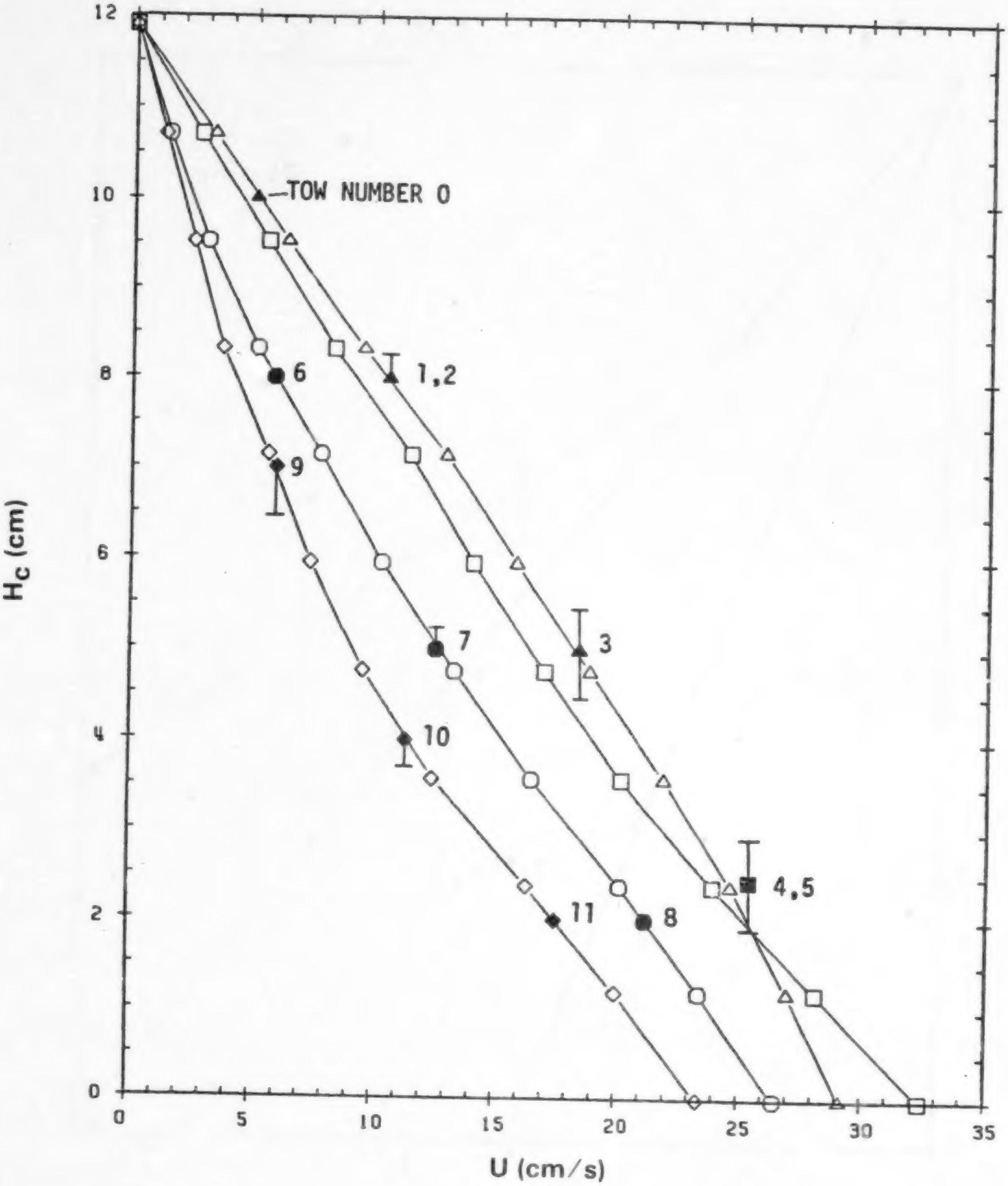

Figure 13. Predictions (open symbols) and observations (closed symbols) of dividing-streamline heights as functions of towing speed of Cinder Cone Butte model.

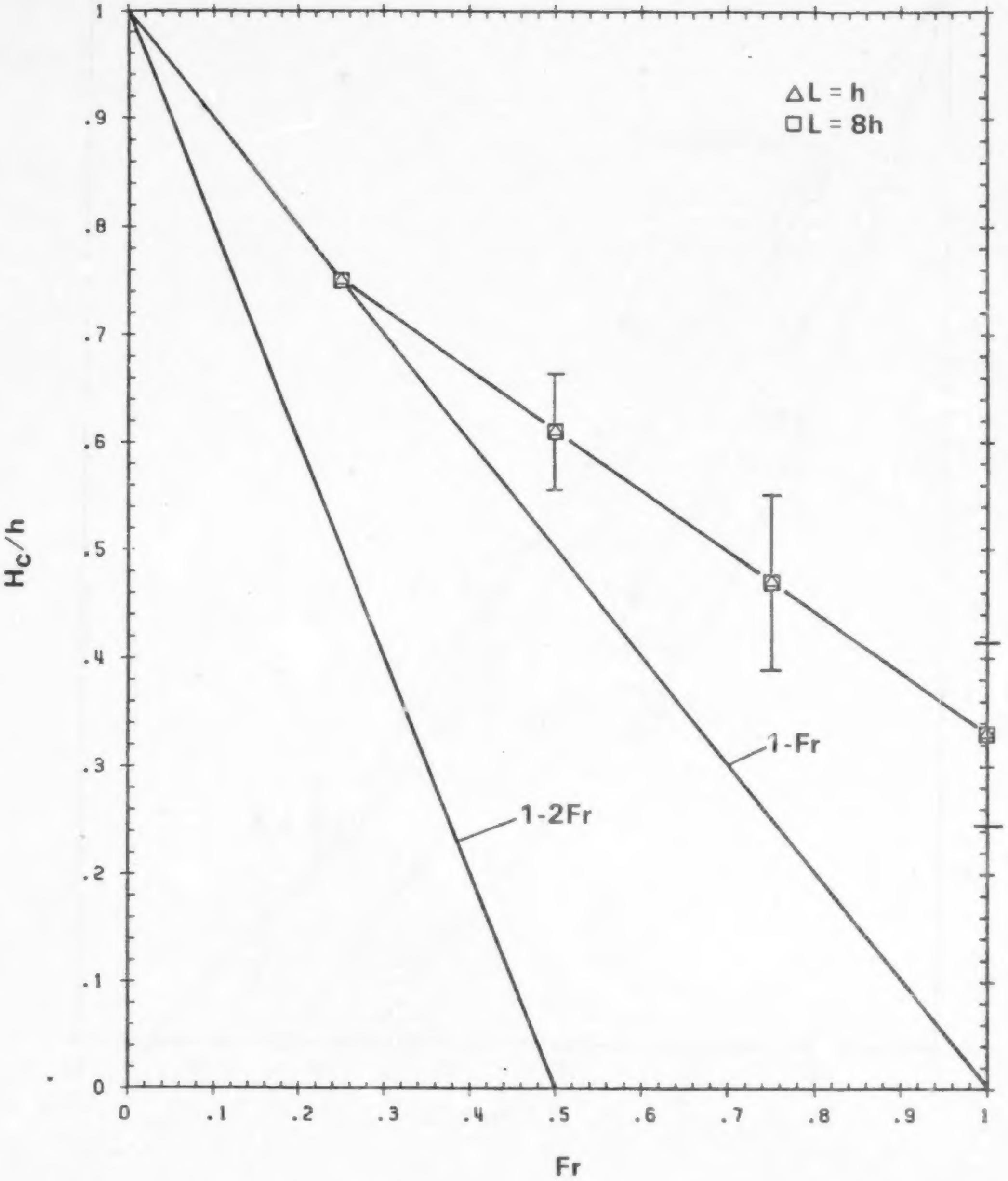

Figure 14. Dividing-streamline height/hill height ratio from triangular ridge study expressed as function of Froude number.

ridges perpendicular to the wind, it was concluded that the aspect ratio, per se, does not have a significant influence on the dividing-streamline height H_c. Deviations from the $H_c/h = 1-Fr$ rule are attributed to the combination of shear in the approach flow and the steep slope of the triangular ridges, which resulted in the formation of an upwind vortex with downward flow on the front face of the ridges. The "1-Fr" rule was validated for the sinusoidal ridge with a length-to-height ratio greater than 16:1; in this case, the shear in the approach flow was much less pronounced and the upwind slope was substantially smaller. Note that the above deviations from the "1-Fr" rule do not invalidate Sheppard's concept. The rule should be interpreted as a necessary but not sufficient condition, i.e., a fluid parcel may possess sufficient kinetic energy to surmount a hill, but it does not necessarily do so.

In the Japanese stratified wind tunnel studies (Snyder et al., 1982), a range of operating modes was found that yielded reasonably strong shear layers with depths more than twice the hill heights in conjunction with strong stable temperature gradients. These provided dividing-streamline heights as large as 0.75 h. In the vertical fence (solid wall) studies with a stratified approach flow, the shear was found to have an overwhelming influence. Conclusions are: (1) as in the triangular ridge studies, the crosswind aspect ratio was relatively unimportant, the basic flow structure was independent of aspect ratio; (2) the shear (in conjunction with the steep slope) created an upwind vortex such that plumes were downwashed on the front faces; and (3) under strong enough stratification, there was a limit to the downward penetration of elevated streamlines on the upwind side of the fence; the extent of this penetration was apparently predictable as a balance between kinetic and potential energies. With these same shear flows approaching the much lower sloped Cinder Cone Butte model, however, there was no evidence of upwind vortex formation. Limited concentration measurements on the Butte model suggested that Sheppard's integral formula correctly predicted the height of the dividing streamline.

From the sinusoidal ridge studies with wind angles at other than 90°, it was concluded that the effects of deviations in wind direction (from 90°) are relatively insignificant until the wind direction is something like 45° to the ridge axis. At 30°, significant departures from the $H_c/h = 1 - Fr$ rule were observed. The fluid had sufficient kinetic energy to surmount the ridge but, presumably, found a path requiring less potential energy round the end of the ridge. When the plume streamers were moved closer to the upstream stagnation streamlines (upwind of the upwind edge of the ridge), they behaved according to the $H_c/h = 1 - Fr$ rule.

These experiments suggest that the lateral offset of the source from the (probably contorted) plane of stagnation streamlines is an important parameter to consider in determining the location and value of surface concentrations, especially when the wind is at a small angle to the ridge axis (say, <45°).

The two-dimensional triangular ridge studies showed that steady-state conditions are not established in strongly stratified flows (say, $Fr < 1$). A squashing phenomenon and upstream columnar disturbances continuously changed the shapes of the "approach flow" velocity and density profiles. Thus, these experiments have no analog in the real atmosphere. Further, since long ridges cut by periodic small gaps require very long tow distances in order for steady state to be established, it is concluded that previous laboratory studies may not be representative; specifically the $H_c/h = 1 - 2Fr$ formula proposed for flow about ridges with small gaps is not expected to be valid in the real atmosphere. Finally, a suggestion is made that the gap ratio (the fraction of area removed from a model that spans the width of the towing tank) must exceed 25% in order for steady-state conditions to be established in the usual size and shape of a towing tank. More work is required to establish firmly the relationships between model size and shape, stability, and tank size and shape in order to determine limits of applicability of fluid modeling and ranges of transferability to the atmosphere.

Flows and Diffusion in the Lower Layer

The main characteristic of plumes emitted upwind of a hill but below H_c is that they impinge on the hill surface, split, and travel round the sides of the hill (Figure 12). Upwind, the plumes are largely constrained to move in horizontal planes and vertical diffusion is severely limited. They are frequently rolled up within an upwind vortex as they impinge on the hill surface. The plumes can lose significant elevation in traveling round the sides of the hill (Hunt and Snyder, 1980). Plumes that hug the hill surface leave it at the point where the flow separates (generally 100° to 110° from the upstream stagnation point, much as a streamline separates from the surface of a two-dimensional cylinder). Plumes emitted close enough to the stagnation line tend to be entrained into the wake region and rather rapidly regain their upstream elevation while mixing through the depth of the hydraulic jump. Beyond that point, these entrained plumes tend to be vigorously mixed horizontally across the wake, leading to small wake concentrations. Whether or not they are entrained, plumes are generally affected by vortex shedding or low frequency oscillations of the wake. These wake oscillations appear to induce oscillations in the plume upwind of the hill, causing it to waft from one side of the hill to the other.

Snyder and Hunt (1984) showed that under these conditions ($H_s < H_c$), the maximum surface concentration was essentially equal to the concentration measured at the plume centerline in the absence of the hill (at the same downstream distance). The location of the maximum concentration was on the upstream face. A small lateral displacement of the source from the stagnation streamline did not appreciably change the magnitude of the maximum concentration, but moved its location to the side of the hill. Consequently, small oscillations in wind direction may be expected to result in a covering of the hill with the maximum concentration for short periods, but to significantly reduce the average concentration. Finally, a slightly larger displacement of the source (i.e., a distance comparable to the plume width in the absence of the hill) caused the plume to miss the hill entirely, indicating a very strong sensitivity of surface concentration to wind direction.

Flows and Diffusion in the Upper Layer

In the upper layer (Figure 11), buoyancy and inertial forces control the flow as it passes over the hill. Rowe et al. (1982), Bass et al. (1981), and Weil et al. (1981), have suggested that this upper layer flow is approximately potential flow. However, the stratification above may have important effects on the vertical convergence and horizontal divergence of the streamlines (as well as on the diffusion). A different approximation is to treat plumes in the upper layer as if a ground plane were inserted at the dividing-streamline height. By definition, the dividing-streamline height of the upper layer flow is zero. Therefore, the Froude number of the upper layer flow is unity and the flow must be treated as if $F = 1$.

To test this approximation, Snyder and Lawson (1983) conducted a series of tows in a stably stratified salt-water towing tank wherein the density gradient was linear and the dividing-streamline height was half the hill height. Effluent was released at three elevations above the dividing-streamline height. Pairs of tows were made such that, in one tow, the hill (upside-down) was fully immersed in the water and the towing speed was adjusted to provide a "natural" dividing-streamline surface. In the second tow of the pair, the hill was raised out of the water to the point where only the top half of the hill was immersed, thus forcing a flat dividing-streamline surface, while ll other conditions were maintained identical. Concentration distributions were measured on the hill surface for each pair of tows and these were compared to ascertain effects of an assumed flat dividing-streamline surface as is used in the CTDM model. The first run simulated an emission at 0.6 h, where h is the hill height. The physical model was a fourth-order polynomial (bell-shaped) hill. Concentrations were measured at 100 points on the hill surface.

Figure 15 shows the concentration distributions measured in both the fully-immersed and half-immersed cases for $Fr = 0.5$ and $H_s/h = 0.6$. The most obvious difference between the two cases is the absence of lee-side concentrations below half the hill height in the half-immersed case. Of course, in the half-immersed case, concentrations at positions below half the hill height were zero because that portion of the hill was outside the water. In the fully-immersed case, the plume diffused to some extent below half the hill height around the upwind side, but also this plume "hugged" the hill surface as it was swept down the lee side to a much lower elevation than the release height.

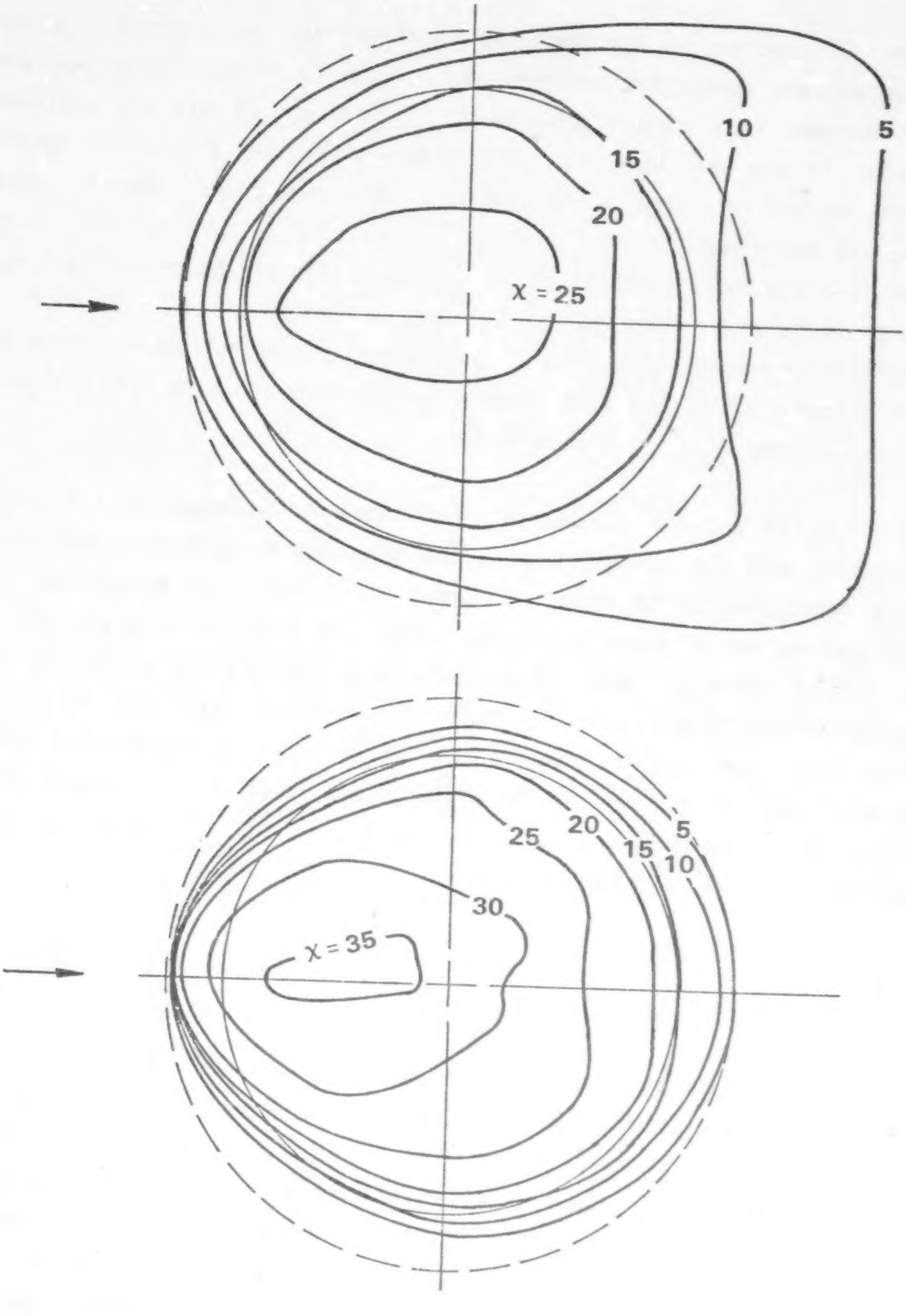

Figure 15. Concentration distributions measured on surface for fully-submerged hill (top) and half-submerged hill (bottom). Arrows indicate flow direction.

Figure 16 presents a scatter diagram comparing, on a point-to-point basis, the surface concentrations measured in the half- and fully-immersed cases. Measurements at points below half the hill height are not included here because, in the half-immersion case, these ports were out of the water. Within the region of large concentrations, the two cases compare quite favorably, the half-immersed case yielding concentrations approximately 10 to 20% larger than the fully-immersed case. In the region of low concentrations, quite large differences occurred (worst case, a factor of 10). However, a close examination showed that in all cases where concentrations differed by more than a factor of 2, the port locations were very close to half the hill height, i.e., either at 0.505 h or 0.59 h.

These results and the results of simulations for releases at 0.7 h and 0.8 h suggested that the assumption of a flat dividing-streamline surface is a reasonable approximation to make, at least with regard to predicting the locations and values of maximum concentrations and areas of coverage on the windward side of the hill. When the stack heights are relatively close to the dividing-streamline height, the lee-side concentrations are also predicted reasonably well. The apparent cause of the relatively poor agreement between lee-side concentration patterns in the higher stack cases is the presence of a hydraulic jump at the downwind base of the hill in the full-immersion case that was absent in the half-immersion case.

Hill Concentrations During Stable Conditions

Again, plumes emitted above H_c are transported over the hilltop; however, if the release height is close to the dividing-streamline height, they spread broadly but thinly to cover the entire hill surface above H_c. Unlike plumes released at or below H_c, plume material reaches the hill surface only by diffusion perpendicular to the plume centerline. Plume meander as observed at or below H_c is absent. As H_s is increased relative to H_c, the point of first contact of the plume with the hill surface moves toward the hilltop. Further increases in H_s move the contact point to the lee side of the hill. These features, in combination with the steadiness in the flow and thus the plume direction, have resulted in some of the largest surface concentrations

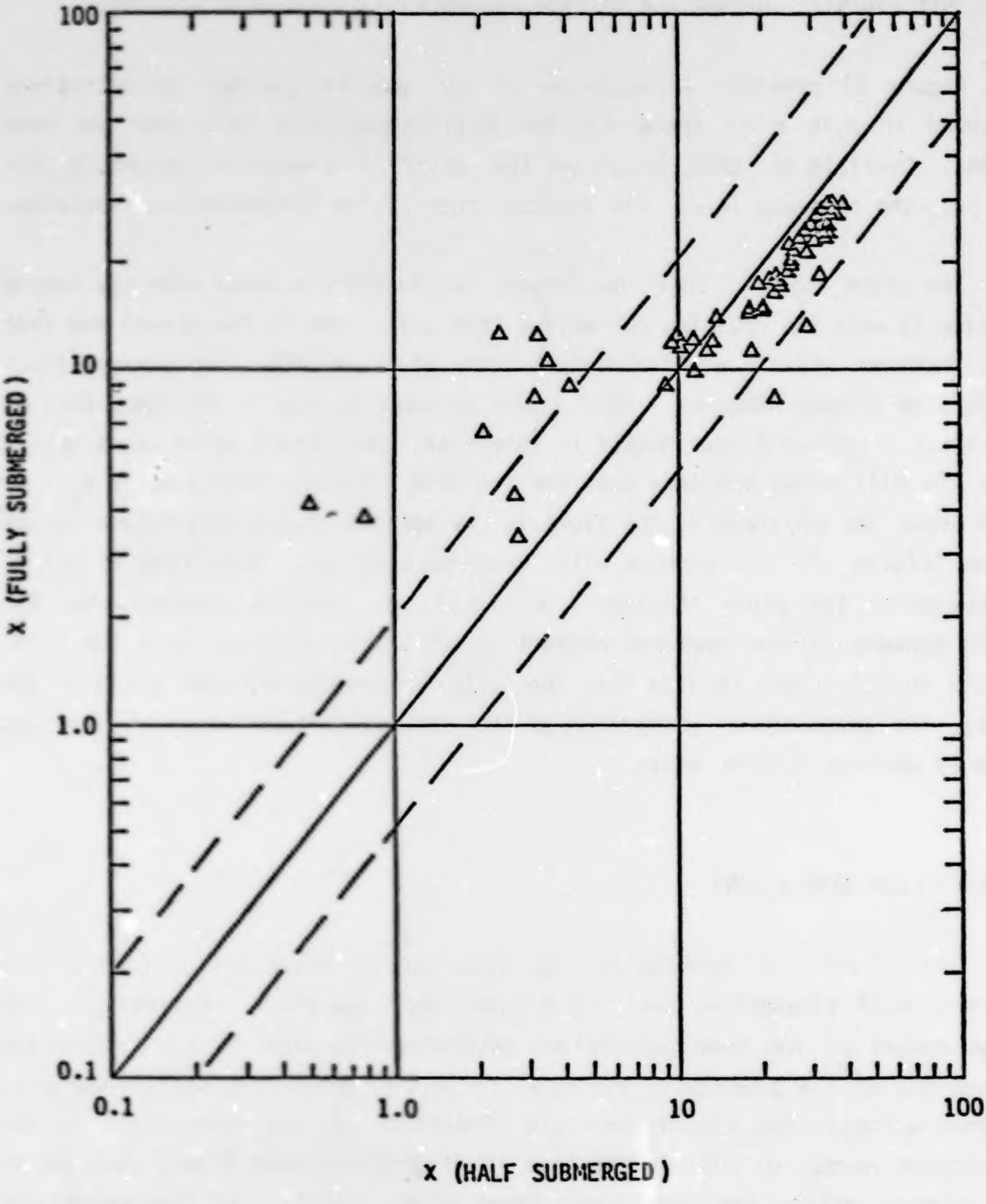

Figure 16. Comparison of surface concentrations for half-submerged versus fully-submerged hill.

observed under any conditions. With still further increases in H_s, the plume moves off the hill surface and surface concentrations diminish rapidly.

Figure 17 presents an overview of the maximum surface concentrations measured in H_c/h x Fr space for the bell-shaped hill of Snyder and Hunt (1984). Overlaid on this graph are the dividing-streamline height ($H_c/h = 1 - Fr$), the boundary layer, and somewhat speculative concentration isopleths.

The graph suggests that the largest concentrations occur when the source release is near the dividing-streamline (the solid line in the graph) and that they decrease rapidly with distance to the right of this line (larger stack heights or Froude numbers). This rapid decrease is due to the fact that as the stack height or Froude number is increased, the contact point moves upward over the hill crest and then down the lee side. Further increases in $H_s - H_c$ much above the thickness of the plume in the absence of the hill result in the plume lifting off the surface with no contact at all. Note that if $H_s - H_c$ approximates the plume thickness, a significant surface concentration can arise because of the downward deflection of the streamlines onto the hill. If the source height is less than the dividing-streamline height (left of the line), the measurements suggest that the maximum surface concentrations are roughly uniform in this region.

NEUTRAL FLOW SIMULATIONS

The effects of terrain on the flow can be demonstrated through the deflection of streamlines over and around ridges and hills. For example, the displacement of the mean streamlines determines how near to the surface the centerline of the plume will reach, which in turn determines the ground-level concentrations. The convergence and divergence of the streamlines in the directions normal to and, in the case of three-dimensional flows, parallel to the surface affect the plume width (Hunt et al., 1979). If flow separation occurs, the size and shape of the recirculating cavity that ensues and the position of the source with respect to this cavity can be very important in determining subsequent plume behavior.

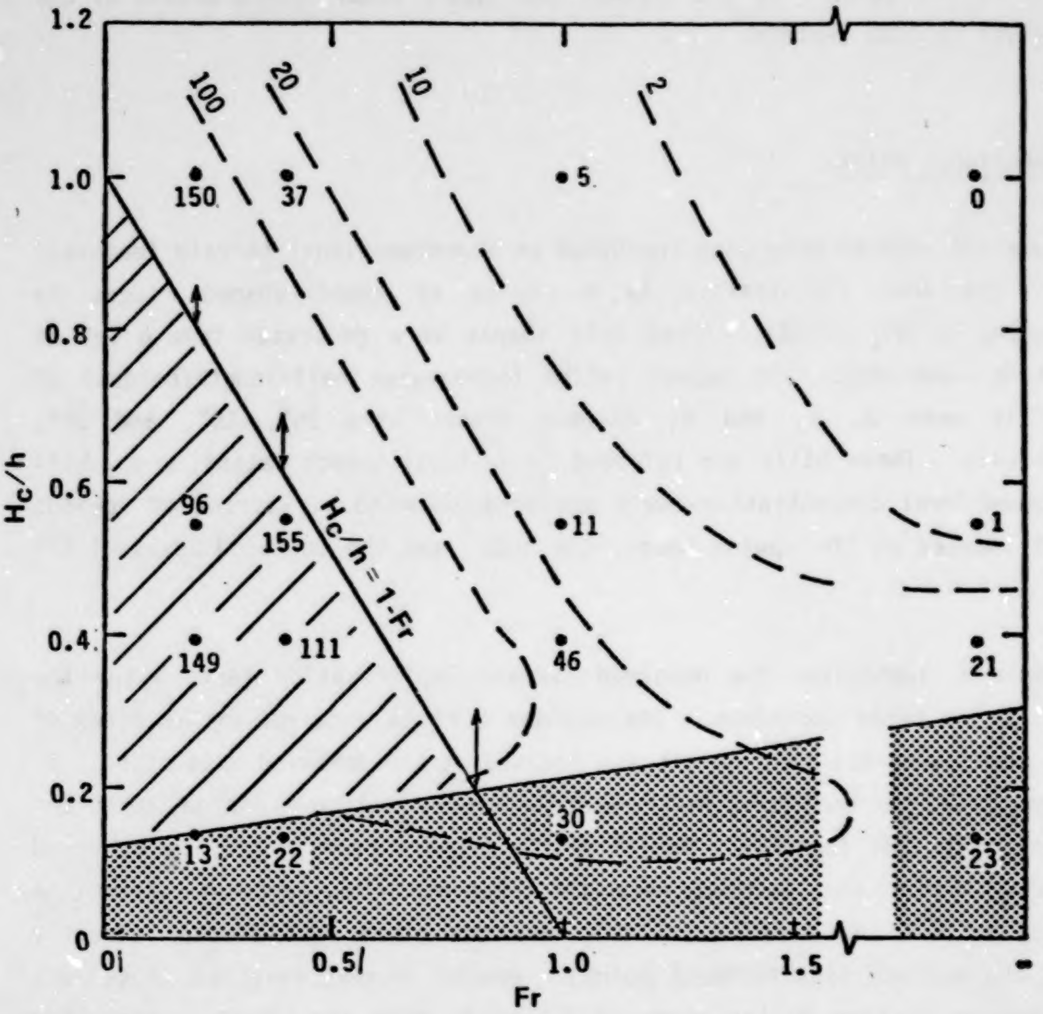

Figure 17. Concentration isopleths (dashed lines) as functions of dividing-streamline height/hill height ratio and of Froude number. Numbers represent concentrations measured at those points. Stippled area depicts surface boundary layer. Striped area represents roughly uniform concentrations. Vertical arrows indicate depth of plume at the location of the hill.

A simple way to evaluate the effects of terrain on ground-level concentrations is to calculate a terrain amplification factor A, which is defined as the ratio of the maximum surface concentration occurring in the presence of the terrain to the maximum that would occur from a source of the same height in flat terrain.

Two-Dimensional Hills

Numerous studies have been conducted on two-dimensional terrain features. Perhaps the most illustrative is a series of smooth-shaped ridges by Khurshudyan et al. (1981). Three hill shapes were generated from a set of parametric equations. The aspect ratios (streamwise half-length/height) of the hills were 3, 5, and 8; maximum slopes were 26°, 16°, and 10°, respectively. These hills are referred to by their aspect ratios, e.g., hill 5. Ground-level concentrations were measured downwind of sources of various heights located at the upwind bases, the tops, and the downwind bases of the hills.

Table 6 summarizes the observed terrain amplification factors for the stacks at the three locations. The maximum A of 15 occurred with a stack of height one-fourth the hill height and located at the downwind base of hill 5. This was due to the very small mean transport but very large turbulent dispersion at that location. Amplification factors nearly as large occurred when the source was located near the separation-reattachment streamline downwind of hill 3, because in this case the plume was advected directly toward the surface (reattachment point). Upwind sources resulted in terrain amplification factors in the range of 1.1 to 3, with the larger values being observed for the steeper hills. Finally, the hilltop source location resulted in amplification factors less than unity, with smaller values being observed for steeper hills.

Three-Dimensional Hills

Two studies have been conducted to determine the effects of the crosswind aspect ratio of a hill (truncated ridge) on dispersion from nearby sources.

TABLE 6. TERRAIN AMPLIFICATION FACTORS FOR TWO-DIMENSIONAL HILLS

Hill	H_s/h	Source location		
		Upwind	Top	Downwind
8	1/4	1.5	0.9	3.4
	1/2	1.1	0.6	3.0
	1	1.5	0.8	2.4
	1-1/2	1.2	0.8	1.7
5	1/4	2.0	0.5	15.0
	1/2	2.0	0.6	8.0
	1	1.7	0.9	5.6
	1-1/2	1.2	1.0	2.9
3	1/4	2.8	0.3	7.5
	1/2	2.5	0.7	6.4
	1	1.8	0.9	10.8
	1-1/2	1.9	0.9	7.8

Triangular ridges of different crosswind lengths were constructed by cutting a cone in half and inserting straight triangular sections between the two halves. Snyder and Britter (1984) investigated surface concentrations on the ridges resulting from upwind sources. Ground-level concentrations were measured downwind of stacks of height 0, 0.5, and 1.0 h, with stacks located 3.7 h upwind of the hill centers.

For the ground-level source, downwind concentrations were reduced by the presence of the hills due to the excess turbulence and divergence of the flow around the hills. For the elevated sources, the maximum ground-level concentrations occurred at the crest or on the lee sides of the hills. The maximum values for the cone were 2 to 3 times those for the two-dimensional ridge and 2 to 4 times those in flat terrain. Castro and Snyder (1982) extended this study by locating sources at various downwind positions. Flow separation was observed on the lee sides of these hills because of the steep lee slopes and the salient edges at the crests.

The cases discussed above are summarized in Table 7 by listing them in order of decreasing A. From the standpoint of a fixed stack height, it appears that the worst location for a source is just downwind of a two-dimensional ridge and the best is on top of a ridge.

TABLE 7. SUMMARY OF TERRAIN AMPLIFICATION FACTORS FOR NEUTRAL FLOW

Source location	Hill type	Amplification factor
Downwind	Two-dimensional	10-15
Downwind	Three-dimensional	5-6
Upwind	Three-dimensional	2-4
Upwind	Two-dimensional	1-3
Top	Two-dimensional	0.5-1

Sources downwind of terrain obstacles generally result in larger surface concentrations because of the excess turbulence generated by the hills and because the effluent is generally emitted into streamlines that are descending toward the surface. Maximum terrain amplification factors are considerably larger downwind of two-dimensional hills than those downwind of three-dimensional hills. A probable cause of this effect is that, in three-dimensional flows, lateral and vertical turbulence intensities are enhanced by roughly equal factors, whereas in two-dimensional flows, the lateral turbulence intensities are not enhanced as much as are the vertical turbulence intensities (because of the two-dimensionality). Since the maximum surface concentration depends upon the ratio σ_z/σ_y (Pasquill, 1974), we may expect the A's downwind of two-dimensional hills to be larger than those downwind of three-dimensional hills. Also, the sizes of the recirculating cavity regions of three-dimensional hills are generally much smaller than those of two-dimensional ridges.

With regard to upwind sources, terrain amplification factors are larger for three-dimensional hills because, in such flows, streamlines can impinge on the surface and/or approach the surface more closely than in two-dimensional flows (see Hunt and Snyder, 1980; Hunt et al., 1979; Egan, 1975).

IMPLICATIONS FOR MODEL DEVELOPMENT

Wind tunnel and towing tank modeling have proved useful in performing generic studies to understand the basic physics of flow and diffusion in complex terrain. The fluid modeling studies have demonstrated the applicability of the dividing-streamline concept to a wide variety of hill shapes, slopes, and aspect ratios. H_c forms the boundary between a lower layer of horizontal flow and an upper layer that passes over the hilltop.

Plumes released in the lower layer impact on the hill surface; the resulting surface concentrations essentially equal those observed at the center of the plume in the absence of the hill. For practical purposes, a plume released in the upper layer can be treated as a release from a shorter stack upwind of a shorter hill, i.e., as if a ground plane were inserted at the dividing-streamline height.

These results are being used directly in the complex terrain modeling approaches and have proved to be quite useful to the modelers. Strongly stratified towing-tank experiments on flows over two-dimensional ridges were found to have no analog in the real atmosphere because of the unsteadiness created by the finite length of the tank. Another limitation of fluid modeling studies is that they cannot simulate the variability of the real atmospheric boundary layer. Reasonable attempts have been made to account for wind direction and speed variability by changing the tow speed and hill orientation. But real atmospheric turbulence, especially low-frequency meandering common in stable conditions, must be kept in mind in transferring the fluid modeling results to the real world.

SECTION 6

MODEL IMPROVEMENT AND RESEARCH NEEDS

Previous sections have described the present state of understanding and of dispersion model development for flow phenomena in complex terrain. This section provides some suggestions, based on the information available, of how the performance of air quality models to be applied to complex terrain settings can be (and are being) improved. Identification of research needs to reach closure on outstanding complex terrain issues is also provided.

USE OF ON-SITE METEOROLOGICAL MEASUREMENTS

A model cannot perform better than allowed by the quality and representativeness of the input information. Experience with the Complex Terrain Model Development field experiments, fluid modeling experiments, and subsequent data analyses shows that to obtain an understanding of plume behavior, one needs to have reliable information about flow conditions. For complex terrain settings especially, one cannot expect that meteorological data obtained for model input from an off-site location is necessarily representative of the local conditions of interest.

Figure 18 compares a wind rose from an on-site meteorological tower at the Westvaco Luke Mill site to the Pittsburgh, Pennsylvania airport rose, which was the nearest National Weather Service observation station. The on-site measurements clearly show the effects of flow channeling in altering the frequency of occurrence of winds by direction. Great uncertainty would need to be associated with model predictions using the off-site Pittsburgh data, about 150 km distant.

Figure 19 from Venkatram et al. (1983) shows the ability to estimate vertical plume spread during stable conditions. This was achieved using on-site σ_w data at Cinder Cone Butte, with the predicted values compared to σ_z derived from various ranges of lidar scan sampling frequencies (scans/hour).

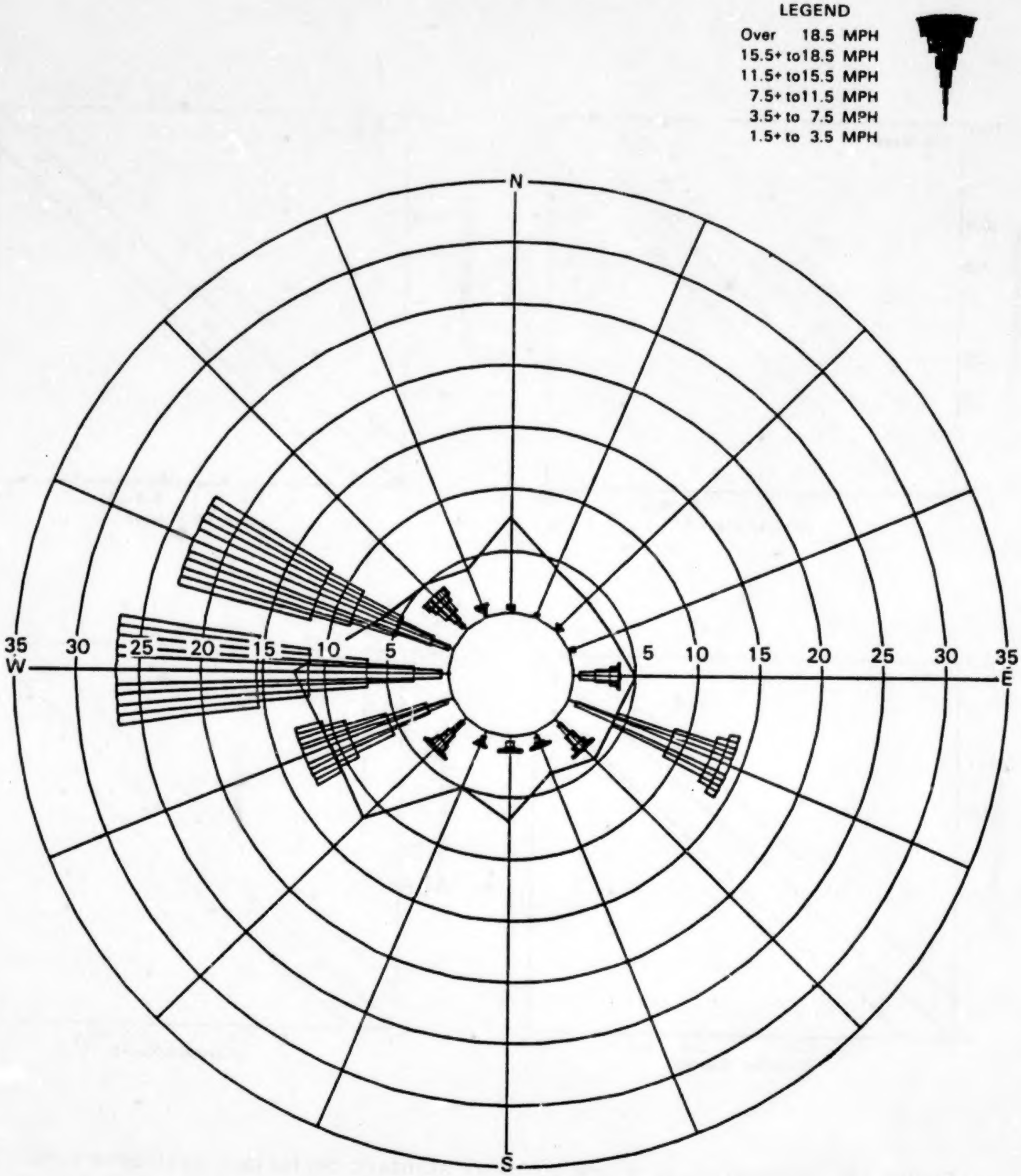

Figure 18. Wind rose from Westvaco Luke Mill meteorological tower for two-year period as compared to Pittsburgh airport wind directions (solid line).

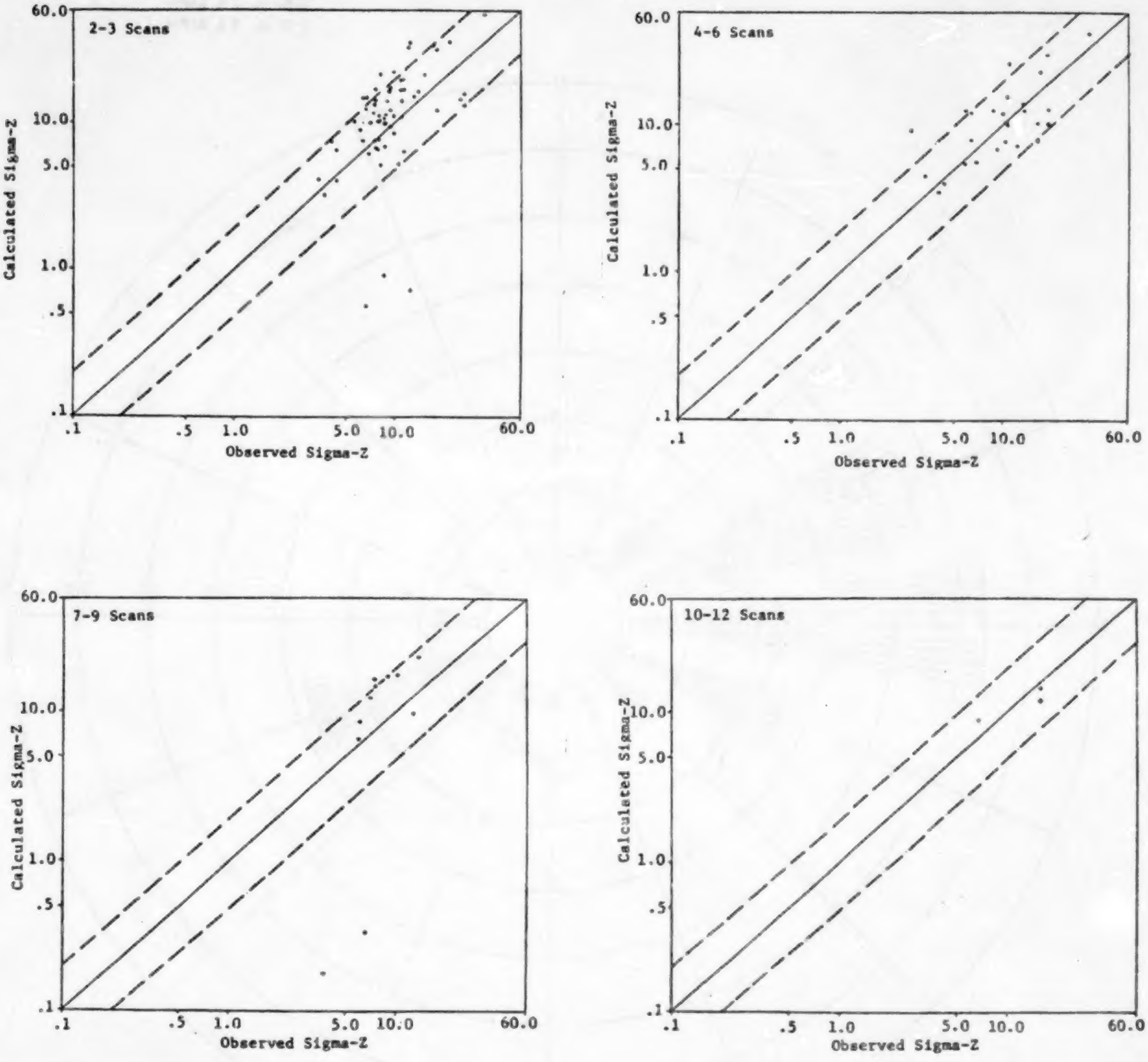

Figure 19. Comparison of plume vertical standard deviations estimated from Equation 34 with those derived from lidar observations at Cinder Cone Butte for ranges of hourly scan frequencies.

The comparison is generally good, especially in the highest sampling rate category of 10-12 scans/hour. During such stable conditions, when the flow aloft is largely uncoupled from the surface, it is especially important to obtain meteorological information (particularly turbulence data) that are representative of conditions at expected plume height.

Hanna (1980, 1983) and Dittenhoefer (1983) have demonstrated that improvements to understanding dispersion rates are possible using on-site turbulence data. Lavery et al. (1983a) have stressed the advantage of using on-site wind direction data to determine probability density functions for direct input to replace the use of σ_y's in modeling applications.

IMPROVED PARAMETERIZATIONS OF STABLY STRATIFIED FLOW TRAJECTORIES

The Complex Terrain Model Development program is yielding considerable information on the behavior of plumes in stable flows. Although further verification work is required, especially for full-scale conditions, it is possible to draw some strongly supported conclusions at this time.

The use of Froude number to characterize the relative importance of inertial versus buoyancy forces on the flow is well established for laboratory-scale experiments and carries over to the scales of the Cinder Cone Butte and Hogback Ridge experiments. The related parameter of critical or dividing-streamline height, H_c, is important in relating the implications of large or small Fr to the expected behavior of an elevated plume. There are alternative forms of defining Fr and H_c, the choice of which depends largely upon the detail of the meteorological data available. The simplified form is

$$H_c = h(1-Fr) \tag{42}$$

where h is a characteristic hill height and Fr = U/Nh, and where N is the Brunt-Vaisala frequency given by

$$N = [(g/\theta(z)\ (\partial\theta/\partial z)]^{\frac{1}{2}} \tag{43}$$

where θ is potential temperature (°K) and U is the characteristic wind speed. This is appropriate for conditions of relatively constant values of wind speed and potential temperature gradient as a function of height.

For more general conditions Snyder et al. (1982) have demonstrated the applicability of solving

$$\frac{1}{2}U^2(H_c) = g\int_{H_c}^{h} \frac{(h-z)}{\theta}\frac{\partial\theta}{\partial z}\, dz \qquad (44)$$

where H_c must be determined iteratively. This is the form of the equation for obtaining H_c that is currently being used in the Complex Terrain Model Development program. Ryan and Lamb (1984) confirmed the superiority of this equation to Equation 42 for arbitrary wind and temperature profiles in the case of the 335-m tall Steptoe Butte.

Recommendations for Flow above H_c

The Cinder Cone Butte and Hogback Ridge field data and fluid modeling results, as well as other model validation evidence, suggest that some modification of flow trajectories to allow lifting of the plume over a terrain object be incorporated into models for plumes in stable flow above H_c. The approach being pursued in the CTDM model is described by the LIFT algorithms in Section 3. Simpler algorithms will also be pursued to ascertain how much parameterization is necessary to provide model improvement. The fluid modeling tests of Snyder and Lawson (1983), demonstrating the limits of applicability of replacing the dividing-streamline height with a flat surface, can be used as guidance in structuring the algorithms for plume heights at varying elevations relative to H_c. The progress achieved in parameterizing the flow above H_c during stably stratified conditions will also be relevant to neutral (and perhaps unstable) flow parameterizations.

Recommendations for Flow below H_c

Field and physical modeling experiments support the contention that plumes transported in a stable flow below H_c can impinge on a terrain feature or can flow around the sides. If impingement occurs, the maximum surface concentrations can be as large as the elevated plume centerline concentrations. The COMPLEX I, COMPLEX II, and SHORTZ models assume a full doubling of the elevated plume centerline concentrations during impaction because full reflection at the surface is assumed. This factor probably contributes to the tendency for these models to overpredict during stable conditions. COMPLEX I and II allow a minimum 10-m standoff distance in the Gaussian exponential term, but this does not affect concentrations very much for most full-scale situations. (This 10-m standoff distance is important for many of the Cinder Cone Butte simulation runs, however.) The RTDM model uses a partial reflection coefficient that depends upon plume growth rate and terrain slope rather than full doubling. The CTDM model uses a spatial integration upwind of the point of plume centerline impingement to calculate the effect of surface reflection on the concentration at the point of interest. An adjustment recognizing the limited effects of reflection is recommended for use in refined models.

The parameterization of the vertical and horizontal dispersion for flow below H_c should account for increased meandering on horizontal dispersion as well as the possibility of increased effective vertical dispersion due to wind shear effects. None of the currently available models formally parameterize these expected changes in σ_y or σ_z due to upwind effects. Models that use on-site turbulence data representative of these conditions should show improved performance, however, because such effects would be reflected directly in the measured values.

IMPROVED PARAMETERIZATIONS OF NONSTABLE FLOW TRAJECTORIES

The COMPLEX I and II models, as well as a number of other models, simulate the effects of deformation of flow passing up and over terrain with "half-height" plume path coefficients. The COMPLEX/PFM model, for certain sets of conditions, uses a potential flow theory to develop more site-specific trajectories and combined deformation effects. It appears to show improvement over COMPLEX I and II. Theory suggests that a plume passing over a two-dimensional ridge would be better described using a terrain-following algorithm versus a half-height correction. However, vertical dispersion rates will be increased due to changes in the boundary layer flow. This will tend to increase the ground-level concentrations upwind over those to be expected in the absence of the hill. More analysis of field and physical experimental data is needed regarding this issue before a specific change to the current EPA models is recommended. Observations during nonstable conditions at the Cinder Cone Butte and Hogback Ridge field experiments are currently available for such analyses.

MODELING NEEDS FOR LEE-SIDE FLOW TRAJECTORIES

Theory and experiments suggest that under different combinations of atmospheric stability, hill size and shape, and location of releases relative to terrain features, the maximum surface concentrations occur on the lee side of the hill (Snyder, 1983). This can occur under stable conditions with the source above the dividing-streamline and upwind of the hill, or under nonstable conditions with the source in the wake cavity region downwind of the hill and below the region of flow separation (Huber et al., 1976). The existence of separation depends upon the slope and shape of the hill, the crosswind aspect ratio, surface roughness, and the degree of air flow stratification. Under neutral conditions, terrain amplification factors as large as 15 have been observed.

As described in Section 5, wind tunnel and towing tank experiments can provide information on the systematic variation of these effects with atmospheric stability and terrain geometry. Field data from the Cinder Cone Butte and Hogback Ridge experiments also contain considerable information on concentrations observed on the lee side for conditions of the source upwind of terrain features. For strongly stable flows ($Fr < 1$) with sources in the lee of terrain, the horizontal flow below the dividing streamline is observed to separate in traveling round the sides of hills, forming horizontally recirculating cavity regions. Effluents from a source placed within such a cavity region will be transported "upwind" toward the hill surface and cover a narrow vertical band spread over a wide sector of the hill surface. Whereas short-term concentrations are likely to be considerably smaller than those from upwind sources (impingement), longer-term concentrations may be larger because, whereas the wind meander will significantly reduce impingement concentrations, such meander will not significantly reduce the concentrations from lee sources. The stratified towing tank provides an ideal setting to examine the potential for large concentrations and to provide physical descriptions and measurements upon which mathematical modelers may construct and/or improve complex terrain dispersion models.

There are two issues that need to be addressed: (1) provide guidance regarding when the maximum concentrations would be expected to occur on the windward side of terrain versus the leeward side for purposes of deciding which aspect should be emphasized in modeling, and (2) develop and validate reliable mathematical algorithms for conditions when the lee-side concentrations are of concern.

FLOW FIELD MODELING NEEDS

To date, the EPA Complex Terrain Model Development study has focused on the dynamics of plume interactions with elevated terrain features under conditions of stable flow toward the terrain. There are many topographical and meteorological settings where stable flows toward the crests of high terrain may occur very infrequently or not at all. Site-specific meteorological data can shed light on this issue for some locations, but a reliable fluid dynamical modeling approach would be a much less expensive alternative means of determining whether or not such flows occur. The ASCOT program (Dickerson and Gudiksen, 1983) has developed models that can be applied to flows within mountain valleys. Wooldridge and Furman (1984) have studied the wind fields around a more isolated terrain feature. A number of wind flow models have been proposed for general use, but comprehensive validation efforts are needed before they could be deemed reliable.

VALLEY VENTILATION MODELING

This review document has emphasized the modeling needs for compliance with the ambient air quality standards. The meteorological conditions that tend to be constraining are those which, for a single source, result in the maximum impact on high terrain. Another air quality issue is the buildup of emissions from multiple sources in a confined valley during conditions of general atmospheric stagnation.

The ASCOT program is developing models for predicting the effects of slope flows and valley drainage winds on dispersion in valleys. However, dispersion models are needed that will couple the effects of synoptic-scale conditions to the overall ventilation rate of valleys having differing topographic features. The EPA Green River Ambient Model Assessment program is one current effort to meet this need, but more field verification of the component models is needed. Similarly, the effort to couple the valley component (VALMET) with the mesoscale component (MELSAR) during conditions of valley out-venting has not yet been completed.

SECTION 7

SUMMARY AND CONCLUSIONS

The purpose of this document was to assess the current understanding of dispersion processes in complex terrain and to assess the ability of currently available or currently-being-developed disperson models to meet EPA regulatory needs. The major findings are summarized below together with associated conclusions.

PHENOMENA OF IMPORTANCE

The primary meteorological conditions of concern for sources located in mountainous terrain settings are those in which plumes are embedded in stable flow that is advecting toward terrain features at or above plume elevation. For some settings, multi-hour persistence of plumes embedded in neutrally stable air flows may also be of paramount concern. Fumigation associated with temperature inversion breakup can be important to still other settings. Multi-source regions need to be concerned about the buildup of pollution in stagnant valleys.

Our knowledge of flow behavior during stable conditions has improved considerably over the past several years, largely as a result of research efforts undertaken including theoretical work, fluid modeling efforts, and field measurement programs. It is now widely acknowledged that stably stratified flow behaves differently depending upon details of the temperature gradients, velocity profiles, and terrain geometry. The effects of stability-related and inertial forces can be parameterized by the Froude number, Fr. The implications on flow behavior at any elevation relative to the terrain depends upon the related parameter H_c, the critical or dividing-streamline height, and the ratios of the hill height to hill length and width. The fluid modeling experiments and field studies show that H_c in particular can be interpreted as a height that separates a lower flow that tends to pass around the side of an obstacle from an upper flow that can flow up and over the top of an obstacle. With these two parameters, it is possible to differentiate the conditions that give rise to direct impingement on windward slopes, passage of a plume up and over a feature, or the drawing down of a plume surmounting the obstacle to pass closely along the leeward slope.

An equally important aspect of modeling the concentrations expected on high terrain is the estimation of atmospheric turbulence levels in both the vertical and horizontal directions. The presence of terrain features upwind of a source is known to disturb the flow by vortex shedding, formation of regions of separation, and the general creation of shear in the flow. The principal effect of upwind terrain is to increase the horizontal dispersion rates over those that would be expected over flat terrain, especially during stable atmospheric conditions. The effect obviously depends upon the nature of the terrain upwind of the region of interest and cannot readily be generalized. A way of incorporating these phenomena into models is by measuring directly the wind direction variations with time and using this information to construct estimates of the crosswind spread or probability density functions for the concentration distributions. Similarly, vertical dispersion rates in complex terrain can differ from those expected over flat terrain due to the creation of shear caused by flow accelerations, decelerations, and distortions in general. Again, direct measurements of vertical wind velocity variations are desirable for purposes of estimating the vertical dispersion rates.

Other phenomena of concern are the effects of flow separation in the lee of terrain features in drawing emissions from sources downwind back to the leeward surface. Observations near existing sources have identified that such recirculation occurs. Fluid modeling efforts have indicated that the magnitude of the concentrations on the leeward faces can be quite large.

The buildup of pollution in deep, contained valleys during conditions of synoptic-scale stagnation is a problem associated with the presence of multiple sources in such settings. Whereas impingement phenomena associated with a single source emitting into stable flows or persistent neutral flows result in peak concentrations over 1-, 3- and 24-hour averaging times, stagnation within valleys can result in the buildup of high concentrations over multi-day periods. A better understanding of the meteorological conditions which are associated with stagnation and with the eventual purging of such regions is needed.

VALIDATION OF AVAILABLE MODELING TECHNIQUES

Although there are a large number of models and model variations in the dispersion modeling community, this review considered only those complex terrain models that are presently being used by EPA in regulatory practice, models presently being developed by EPA, and models submitted to EPA in response to a formal "Call for Models" published in the March 1980 Federal Register. The models received were to undergo model evaluation tests and scientific peer review. Available dispersion models for complex terrain applications are largely adaptations or outgrowths of the Gaussian plume equation approach, although they possess considerably differing levels of sophistication. This is due, in part, to the need to examine extensive time series of meteorological data to estimate the peak 3- and 24-hour and annual averages. Another reason is that very complicated numerical models have not consistently performed better than models of the Gaussian type. Only one non-Gaussian type model was submitted to the EPA in response to the Federal Register "Call for Models." The EPA screening models, COMPLEX I and COMPLEX II, are presently applied by the EPA and sometimes used as reference models in model comparison studies. Current guidance allows the use of alternative models in regulatory applications if such an alternative model is shown to be superior in source-specific model validation programs.

TRC Model Evaluation Efforts

Under contract to the EPA Office of Air Quality Planning and Standards, TRC Environmental Services, Inc., performed a statistical evaluation of the currently available EPA complex terrain dispersion models and the models submitted in response to the Federal Register notice. A preliminary review of the statistical results suggests the following observations based upon a review of the bias and total r.m.s. errors tabulated for each model.

(a) The COMPLEX II model overpredicted the observed highest concentrations for both the Westvaco and the Cinder Cone Butte data sets. It generally rated the most poorly among the Gaussian plume type models.

(b) The COMPLEX I model showed improvement over COMPLEX II, but it overpredicted the largest concentrations at Westvaco by a significant factor. The improvement over COMPLEX II is probably associated with the use of sector averaging in parameterizing the crosswind spread of the plume.

(c) The EPA model, COMPLEX/PFM, performed somewhat better than COMPLEX I and II, which have the same algorithms for many of the meteorological conditions. The differences in the algorithms, which should be associated with the improvements, are in the use of the dividing-streamline height H_c in defining flow regimes for certain meteorological conditions and in the associated use of potential flow theory to estimate plume trajectories and dispersion adjustments for flows above H_c.

(d) The SHORTZ model contains a direct-impaction assumption for both stable and nonstable conditions. It uses on-site turbulence measurements directly to predict dispersion rates rather than identifying stability classifications for these purposes. This model tended to overpredict for both the Westvaco and Cinder Cone Butte data sets but to a lesser degree than COMPLEX II and to a lesser degree for Westvaco than COMPLEX I. The use of turbulence measurements may account for its improved performance over COMPLEX I and II.

(e) The RTDM and 4141 models performed generally better than the other models for the Westvaco data set. The RTDM model contains consideration of Froude number and dividing-streamline heights. It also allows the use of on-site turbulence data directly to estimate dispersion rates. RTDM performed well also at Cinder Cone Butte.

The 4141 model uses the Pasquill-Gifford dispersion coefficients with a 0.25 plume path coefficient for stable flow. The combination of parameters worked reasonably well at Westvaco but did not result in superior performance when applied to the Cinder Cone Butte data.

(f) The PLUME5 model generally showed the most consistent, average-level performance for the Westvaco data set except for achieving minimum bias for the category of all values paired by time and space. PLUME5 performed less well when applied to the Cinder Cone Butte data.

(g) The IMPACT model, a "K-theory" numerical model, was tested for computational economy on only one-fifteenth of the entire Westvaco data set. The other seven models were also run on this reduced data set. (All eight models, including IMPACT, were run on the entire Cinder Cone Butte data set.) In comparison to the other models, IMPACT performed less well on the Westvaco data subset. On the other hand, it performed better than RTDM for some statistical performance measures on the Cinder Cone Butte data set. The reasons for the difference in performance for the two data sets has not yet been determined.

The tentative interpretations of this model evaluation study support the concepts of the use of the dividing-streamline height and the parameterization of plume trajectories on the basis of H_c during stable conditions. Other things being equal, the use of on-site turbulence data appears to improve model performance. This latter factor is also associated with the models (RTDM and SHORTZ) that showed the most consistent, better-than-average performance both at Westvaco and at Cinder Cone Butte.

ERT Model Evaluation Efforts

Model evaluation work performed on the Cinder Cone Butte base and in association with the EPA Complex Terrain Model Development program shows that the inclusion of H_c in the structure of the model to differentiate between two distinct flow regimes, and the explicit use of on-site meteorological data improved model performance.

The CTDM(11083-E) model generally performed better than Valley, COMPLEX I, and COMPLEX II, especially for the more stable hours. However, CTDM (11083-E) tended toward underestimation during the less stable hours. The latest version of CTDM, incorporating a better formulation of terrain effects and revised formulations of σ_y and σ_z, no longer exhibits such a strong tendency toward underestimating the less stable hours.

Both COMPLEX models tend toward overestimation. COMPLEX II is decidedly worse, especially at low wind speeds (very stable). This is apparently the result of the COMPLEX impingement algorithm in combination with Pasquill-Gifford σ_y and σ_z coefficients for stable conditions. COMPLEX I fares better due to its 22.5° sector averaging in the crosswind direction. Even so, COMPLEX I tends to overestimate by greater margins as H_c increases.

FLUID MODELING SIMULATIONS

The use of fluid modeling techniques in wind tunnels and towing tanks provides powerful tools to test theoretical development work and to investigate systematically the effects of changes in flow conditions, terrain geometry, and the addition or subtraction of complicating factors in flows. While field experiments provide the ultimate test, the impossibility of controlling the meteorological conditions that occur limits systematic investigations of the effects of different conditions to only those captured in a given experiment. Field verification studies are necessary, however, to assure that the results of laboratory experiments apply to full-scale phenomena.

In the EPA Complex Terrain Model Development program, integral use of fluid modeling has been accomplished via experiments performed at the EPA Fluid Modeling Facility. Experiments have been performed to test the applicability of results in several research areas:

(a) Applicability of Dividing-Streamline Concept. Tests have been performed to test the applicability of the dividing-streamline concept H_c for several hill slopes and aspect ratios ranging from ridges to hemispheres and including a scaled model of Cinder Cone Butte. The concept of H_c was found to be valid when interpreted as a necessary but not sufficient condition for a wide range of geometries and flow profiles.

(b) Flow Behavior Above and Below H_c. The behavior of the flow above and below H_c as described in the discussion of phenomena was investigated systematically with towing tank experiments.

(c) Hill-Surface Concentrations. Towing tank and wind tunnel experiments have been used to show that when a plume is embedded below H_c and the stable flow impinges upon a hill surface, the maximum ground-level concentration to be expected is about equal to the centerline concentration expected in the absence of the hill. Full doubling due to "reflection" effects does not occur under these circumstances.

(d) Flat Dividing-Streamline Surface. Experimental results with a fully- and half-submerged model of a bell-shaped hill support the notion that the dividing streamline acts somewhat as a solid (or flat) surface for purposes of simulating the effect on flow trajectories above H_c and not far into the wake of the object. This concept can greatly simplify the mathematical algorithms needed to parameterize the effects of H_c in dispersion models.

(e) Lee-Side Effects. Quantification of the terrain amplification factors associated with the placement of sources in the lee of terrain features having separated flow regimes was performed in the wind tunnel. The tunnel allows a systematic investigation of these effects to be performed as a function of hill shape, relative stack height, etc.

(f) Limitations to the Use of Fluid Models. Strongly stratified towing tank experiments on flows over two-dimensional ridges were found to have no analog in the real atmosphere because of the unsteadiness created by the finite length of the tank. Another limitation of fluid modeling studies is that they cannot simulate the total variability of the real atmospheric boundary layer. Reasonable attempts have been made to account for wind direction and speed variability by changing the tow speed and hill orientation. But real atmospheric turbulence, especially low-frequency meandering common in stable conditions, must be kept in mind and accounted for separately in transferring the fluid modeling results to full-scale flows.

MODELING IMPROVEMENT AND RESEARCH NEEDS

The first recommendation is to encourage the continuation of the current close coordination of research efforts involving mathematical modeling, laboratory experiments, and field studies. Integrated programs that recognize the attributes and limitations of each of these tools have a high probability of success.

In addition to the above, some other specific recommendations are made.

(a) Stable Plume Impingement. The dividing-streamline concept has been reasonably well established through laboratory studies and supported through field studies. Full incorporation of the concept into mathematical models is currently proceeding. Fluid modeling research in this area should be closely coordinated with mathematical modeling to provide very specific guidance and data for validation of modeling concepts and techniques, both for sources below the dividing-streamline height, where the plume will impinge on the windward face of the hill, and for sources somewhat above the dividing-streamline height, where the maximum concentration may occur on the lee side of the hill. Verification at a full-scale site is underway and will be necessary to assure users of the relevance to situations where the ratio of dividing-streamline height to lower boundary-layer height is larger.

(b) Use of On-site Meteorological Measurements. In complex terrain settings, the spatial and temporal variability of flow conditions is very different from conditions over level terrain. Therefore, the use of on-site meteorological data, especially turbulence information, is highly recommended as the basic input information for complex terrain dispersion models. Models that use these data appear to perform better and more consistently that those that do not.

(c) Modeling Needs for Predictions During Neutral and Transitional Conditions. The primary focus for the EPA Complex Terrain Model Development program has been the phenomena associated with stable atmospheric conditions. The bulk of the experiments were performed during nighttime hours. Some data are also available for analysis of the flow phenomena during the morning transitional hours and other hours of steady neutral flow. For topographic settings where persistent neutral conditions or transitional fumigation are important, model algorithms developed on the basis of these data would be appropriate. For moderately stratified flows (Fr > 1), plume path coefficients need to be determined as functions of the approach flow stratification and the hill shape (slope and crosswind aspect ratio) so that refined parameterizations may be included in mathematical models. Currently available models typically include only a half-height plume correction for neutral or unstable conditions and for stable conditions when the plume height is above the dividing-streamline height. Fluid modeling research could provide data for a much improved parameterization of the effects of stratification (from neutral through strongly stable) and hill shape on plume trajectories (streamline displacements) and plume deformations (streamline deformations).

(d) Modeling Needs for Predictions of Lee-side Phenomena. The presence or absence of separation on the lee side of a hill will have dramatic consequences on plume behavior from both upwind and downwind sources. The existence of separation, however, is dependent upon the slope of the hill, the crosswind aspect ratio, the stratification of the approach flow, and the surface roughness of the hill, and may be conditional upon the existence of a salient edge from which the flow may separate. The stratification may either enhance or inhibit separation. The stratified towing tank provides an ideal setting wherein each parameter may be controlled and varied independently so that the parameter space in which separation occurs can be determined. Under neutral conditions, recent fluid modeling studies have shown that very significant terrain effects are observed when sources are placed downwind of hills where the flow separates steadily or intermittently. Terrain amplification factors as large as 15 have been observed. Fluid modeling research should be continued to map the fields of terrain amplification factors as functions of hill shape and slope.

(e) Modeling Needs for Predictions During Stagnation Conditions in Deep Valleys. The DOE ASCOT program is addressing the dynamics of local flows and drainage winds in valley settings primarily associated with western energy development activities. When this work nears completion, efforts will be needed to transfer the results to more general valley settings. Fluid modeling research can provide useful input on the phenomena associated with coupling/decoupling between free-air cross-valley winds and valley drainage flow regimes, including the case of a stagnant air mass trapped within a valley.

EPA REGULATORY APPLICATIONS

As mentioned in Section 4, a separate scientific review is being performed by personnel in the EPA Meteorology and Assessment Division of the complex terrain dispersion models submitted for testing in response to the March 1980 Federal Register "Call for Models" notice. This separate, independent review will be based on an interpretation of the TRC statistical evaluations and on a review of the theoretical bases on the model algorithms. The findings from both the TRC and ERT evaluations that are contained in this assessment document are stated in relatively general terms and can be expected to be qualified or altered after the more comprehensive review is completed.

Identification of existing dispersion model(s) with the best overall statistical performance is expected to arise from a consideration of the results presented in this assessment document combined with the conclusions formulated by the EPA inhouse review of the TRC model evaluations. The various statistical performance measures of the superior model(s) must then be ranked based on their relative importance to statutory requirements in order to select the "best" complex terrain dispersion model to meet EPA regulatory applications.

In addition to this current evaluation process, the EPA Office of Research and Development is actively pursuing improvements to existing dispersion modeling capabilities through the Complex Terrain Model Development program. The goal of this program by 1986 is the development of models with known accuracy and defined reliability for simulating 1-hour average concentrations resulting from plume impingement on elevated terrain obstacles during stable atmospheric conditions. Future objectives of this program may include extension of the complex terrain model development effort to increased topographical complexity (e.g., lee side impingement), to neutral and unstable atmospheric stabilities, and to longer averaging periods.

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